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THE RATE OF DECOMPOSITION OF PLANT ROOTS[1]

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The rate of decomposition of plant material when incorporated with the soil has been the subject of many investigations. These have dealt almost entirely with the aerial portions of the plants and give little or no data pertaining to the decomposition of the crown and roots. As the use of grasses and legumes is widely advocated for the control of soil erosion by wind and water and for increasing the organic matter content of the soil, the rate of decomposition of the roots is of particular importance.

Data are presented in this paper showing the relative rates of decomposition of the crown and roots of: alfalfa, *Medicago sativa* L.; slender wheat grass, *Agropyron pauciflorum* (Schwein) Hitchc.; brome, *Bromus inermis* Leyss.; crested wheat grass, *Agropyron cristatum* (L.) Beauv.; and thread leaved sedge, *Carex filifolia* Nutt., (a common native plant in the drier portions of the prairies, generally included with the grasses).

METHODS

Samples of sod were collected from areas supporting a pure stand of the different plants, the aerial portions of which were cut off just above the crown; the crown and roots were then washed free of soil and air dried. A portion of this material was ground in a hammer mill until it would pass a 1.5-mm. sieve; this fine material was used in method A. Another portion was cut into pieces from 1 to 2 inches long and run over a 2-mm. sieve to remove the finer particles; the coarse material remaining on the sieve was used in method B.

A. *Evolution of Carbon Dioxide*

Two-gm. samples of the finely ground materials were mixed with 150 gm. of soil and placed in Erlenmeyer flasks. The soil was moistened with distilled water, and the flasks were suitably stoppered and kept in a dark cupboard. The evolution of carbon dioxide was determined by aeration of the flasks at periodic intervals, the carbon dioxide being absorbed in 0.5 N NaOH in a bead tower. After absorption of the carbon dioxide, $BaCl_2$ was added to the NaOH solution to precipitate the carbonate, and the excess NaOH titrated with 0.5 N HCl using phenolphthalein as indicator. Aerations were made daily for the first 10 days, after which the period between aerations was gradually lengthened as the evolution of carbon dioxide decreased.

[1] Contribution from the Experimental Farms Service (P.F.R.A.), Dominion Department of Agriculture, Ottawa, Canada. Read to the Soils Group of the Canadian Society of Technical Agriculturists at the Twentieth Annual Meeting at Winnipeg, Man., June 19 to 22, 1940.

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B. *Recovery of Undecomposed Material*

Fifteen-gm. samples of the coarse materials were mixed with 1500 gm. of soil which had passed a 1-mm. sieve and placed in porous clay flower pots. The pots were kept in the greenhouse for a period of 5 or 6 months, water being added whenever the soil appeared dry to simulate the natural wetting and drying that occurs in the field. At the end of the decomposition period the soil was thoroughly air dried and run over a 1-mm. sieve. The majority of the undecomposed plant material remained on the sieve, while the soil passed through. The plant material was dried at 105° C. and weighed, then ignited in a muffle furnace and reweighed. The loss in weight was assumed to represent the undecomposed plant material. While this method is subject to criticism in that some undecomposed material passed through the 1-mm. sieve and the loss on ignition is not a true measure of organic material, the results were in keeping with method A. The conditions for decomposition were more nearly like field conditions than when the plant material was all reduced to the same degree of fineness. This method requires much less work than the determination of the carbon dioxide evolved.

Nitrogen was determined by the Gunning-Hibbard method except that selenium powder was included with the salt mixture to reduce the time required for digestion.

Carbon was determined by the wet combustion method for organic carbon in soils outlined in Methods of Analysis, A.O.A.C., 4th edition, 1935.

RESULTS

The data in Table 1 show the total carbon dioxide produced by the different plant materials during various periods of time. The alfalfa roots produced the most carbon dioxide, while the sedge produced the smallest amount. Slender wheat grass was the second highest, with brome and crested wheat grass approximately equal and slightly below the slender wheat grass.

The data show that after a period of 59 days the evolution of carbon dioxide proceeded at a fairly uniform though much slower rate, indicating that the majority of the easily decomposed material had been destroyed. The amount of carbon dioxide produced by the alfalfa, brome, and crested wheat grass was approximately equal during this period, with the sedge and slender wheat grass decomposing at a slower rate. The slow rate of

Table 1.—The rate of decomposition of the crown and roots of plants as measured by the production of carbon dioxide

Crown and roots of	Total CO_2 produced in the following days							
	14	28	42	59	70	84	105	133
	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
Alfalfa	1157	1471	1613	1683	1726	1767	1801	1842
Slender wheat grass	526	748	858	920	958	985	1007	1029
Brome	374	539	637	709	761	799	832	877
Crested wheat grass	372	509	603	675	722	755	794	831
Thread leaved sedge	200	335	396	418	432	442	446	450

TABLE 2.—DECOMPOSITION OF THE CROWN AND ROOTS OF PLANTS AS MEASURED BY THE RECOVERY OF COARSE MATERIAL AFTER AN INCUBATION PERIOD OF 143 DAYS

Crown and roots of	Added	Recovered	Recovered	Decomposed
	gm.	gm.	%	%
Alfalfa	15.0	4.50	30.0	70.0
Slender wheat grass	15.0	3.57	23.8	76.2
Brome	15.0	5.55	37.0	63.0
Crested wheat grass	15.0	5.50	36.7	63.3
Thread leaved sedge	15.0	10.35	69.0	31.0

TABLE 3.—THE TOTAL CARBON AND NITROGEN AND THE CARBON-NITROGEN RATIO OF THE PLANT MATERIAL

Crown and roots of	Carbon	Nitrogen	C/N
	%	%	
Alfalfa	42.2	1.98	21.3
Slender wheat grass	35.1	1.46	24.0
Brome	36.2	1.16	31.2
Crested wheat grass	29.4	.98	30.0
Thread leaved sedge	41.2	.91	45.2

decomposition of the sedge is of particular interest, for this is a common native plant in the drier portions of the prairies and it may have played an important part in building up the organic matter in the native sod.

The data in Table 2 show the percentage decomposition after a period of 143 days as measured by method B. These results are in keeping with Table 1, except in the case of the alfalfa roots. This discrepancy is attributed to the fact that the pieces of alfalfa roots were much coarser than the roots of the other plants. In the first experiment (A) the roots had all been reduced to the same degree of fineness, thus presenting more uniform conditions for bacterial activity.

Spaulding and Eisenmenger (2) found that the rate of decomposition of different types of plants when incorporated with the soil varied according to the chemical composition of the plant. Material containing a high percentage of nitrogen generally decomposed more rapidly. The content of lignin and pentosans also exerted some influence. The work of Millar, Smith, and Brown (1) showed that the plants with a narrow carbon-nitrogen ratio decomposed more rapidly during the early part of the period but that the reverse was true in the latter stages. Waksman and Tenney (3) also report that the rapidity of decomposition was influenced by the nitrogen content.

The amount of carbon and nitrogen in the plant material was determined to find if the rate of decomposition was in keeping with the carbon-nitrogen ratio. The results of these analyses are reported in Table 3. The data show that the carbon-nitrogen ratio was in keeping with the

rate of decomposition as measured by the evolution of carbon dioxide. No data are available in regard to the chemical composition of the crown and roots at different stages of growth. Variations due to this factor might cause some difference in the carbon-nitrogen ratio and carbon dioxide evolution, though all results to date indicate the same relative order in the rate of decomposition.

Some preliminary work indicates that the rate of decomposition of the crown and roots of spear grass (*Stipa comata* Trin. and Rup.) lies between that of the sedge and crested wheat grass, while blue-joint (*Agropyron Smithii* Rydb.) has approximately the same rate as crested wheat grass and brome.

SUMMARY

Data are presented showing that there was considerable variation in the rate of decomposition of the crown and roots of the plants studied. The crown and roots of thread leaved sedge were the most resistant of the plant materials used. The rate of decomposition was comparable to the carbon-nitrogen ratio, being more rapid in the material with the narrower ratio.

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A SOIL FERTILITY SURVEY BY RAPID CHEMICAL TESTS[1]

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"Soil fertility" may be defined in two ways: (1) The capability of the soil to produce crops; or (2) the richness of the resources of the soil. The former definition is the more comprehensive of the two. Actually, it includes the second, along with such factors as climate, physical condition and moisture-holding capacity. The second is somewhat narrower in scope, but embraces factors which set fairly definite limits on the quantity and quality of crops produced. In this paper, we have adopted the latter meaning, that is, this survey is one of "the richness of soil resources." The results are intended to assist in answering such frequent questions as: "What is lacking in my soil?"; "What should I add to make my soil more productive?"; "What kind of fertilizer should I use?", etc.

A survey such as that undertaken by Chapman and Putnam (1) is very valuable in mapping and classifying a region into land types, and also gives considerable information regarding the fertility levels of those types. In a more detailed soil survey where the soils are classified and mapped on a scale of 1 inch = 1 mile, or even greater scale, and samples are taken from each type and analysed, still more information is gathered. However, the individual farmers are the ones who eventually put any recommendations into practice. This they are more likely to do if the recommendations are based on results of analyses of samples taken from their own farms.

The present survey, the first of its kind in Ontario, covered the county of York, incidently one of the oldest agricultural regions of the province. The production of fluid milk for the city of Toronto, which is within the county, is one of the most important lines of agricultural activity. Some of the lighter textured soils in the southern and central regions are devoted to truck crops.

The project was undertaken in the early fall of 1939 at the request of the Agricultural Committee of the York County Council, and was carried out by the Soils Division of the Department of Chemistry, Ontario Agricultural College, in co-operation with the Agricultural Representative[4] and the farmers of York County. It was sponsored financially by the York County Council and the Ontario Department of Agriculture. In order to acquaint the farmers with the testing program, a series of about fifteen meetings was arranged at community centres throughout the county. These meetings were advertised in the farm press and by circular letter, and were addressed by either a member of the Soils Division or by the Agricultural Representative, in most cases by both. The discussion of the purpose and plan of the survey ran somewhat along the following lines:

"Many farmers are finding that their crop yields and, in some cases, the quality of crops, are not as high as formerly. Some complain that their crops lack feeding value, while others are experiencing difficulty in getting

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satisfactory catches of clover. To assist you in overcoming these problems by giving you first hand information on the fertility levels of your own soil, we are extending our facilities for soil analysis to you, but we are asking that you co-operate by taking your own samples according to our instructions. We request that for each field you decide to sample, you fill out a column of one of these sheets[1], carefully answering all questions asked, and giving the exact location (Lot and Concession number) of your farm. Take the samples according to the instructions on the second sheet and put them in these cardboard boxes, labelling them as directed."

About 600 farmers took advantage of this co-operative scheme. This represents about 10% of the farmers of the county. About 2,700 sample boxes were requested, or an average of 4 or 5 per farmer. Approximately 2,000 samples were actually taken and forwarded to the laboratory for analysis. A few of these were taken from outside the borders of the county.

METHODS OF ANALYSIS

The samples were sent to the office of the county representative, who forwarded them to the College. Upon being received at the laboratory, they were dried (if necessary), prepared and returned to the original boxes to await analysis. The boxes were sorted and grouped according to townships to facilitate compilation of the completed data. The chemical tests, all carried out by the same two men, using a carefully standardized procedure, consisted of determinations of the following soil constituents: 1. Water soluble calcium; 2. Water soluble magnesium; 3. Dilute acid soluble phosphorus; 4. Replaceable potassium; 5. Active organic matter. In addition, the reaction and texture were also determined and recorded. A brief description of the methods of analysis has been appended. In the Appendix will be found also the limits and ranges of the fertility ratings (VL, L, M, etc.) used to classify the samples on the basis of the rapid test results.

DISCUSSION OF RESULTS

The results of such a survey are of value primarily to the farmer who, having been sufficiently interested to collect soil samples, naturally wishes to know the results of the analyses of his own samples and to benefit by any advice as to general farming practices and fertilizer treatment based upon them.

The soil specialist has also much to gain from a study of such results. As a potential source of wealth, the soil ranks foremost among the country's resources, and marked depletion of any essential element necessitates a readjustment of the management of the soil to take care of this depletion. It is the duty of soil workers, therefore, to gain all possible information relative to this problem as a contribution to agricultural stability. Through the type of survey described, a great deal of essential information becomes available, of value not only for the purpose just outlined, but of assistance also in evaluating and improving existing methods of soil analysis.

A brief description of the handling of the first mentioned phase of the work will probably be of some interest. The analyses having been completed, the next task was to make fertilizer and cropping recommend-

[1] Copies of instructions may be secured from the senior author.

ations based on the information supplied and on the analytical results. These data, recorded on the original sheet accompanying each sample, were transferred to other sheets (in duplicate) which were forwarded to the York County Agricultural Representative. He kept one copy of each and distributed the other to the farmer, discussing individual problems where required and generally assisting in the interpretation of recommendations. Individual attention was particularly necessary in those cases where only general recommendations could be given by the College.

The soil specialist is more interested in a summarized statement of results. We shall now, therefore, examine the accumulated data as a whole, and attempt to draw conclusions regarding the fertility trends. Samples were grouped according to texture, the groups being *(a)* sands and sandy loams, *(b)* loams and *(c)* silt loams and clay loams. Fertility ranges or ratings (very low, low, medium, high and very high) were established for each constituent as shown in the appendix. The percentage of samples of each textural group falling in the various fertility categories is shown in the accompanying Table 1 and Figure 1.

TABLE 1.—THE PERCENTAGE OF SAMPLES IN THE VARIOUS FERTILITY RATINGS, BY TEXTURAL GROUPS

Fertility Ratings	412 sands and sandy loams	688 Loams	837 silt and clay loams
	%	%	%
Reaction			
High	18	13	16
Medium	80	86	80
Low	2	1	4
Calcium			
Very high	2	1	2
High	75	75	68
Medium	22	23	27
Low	1	1	3
Very low	0	0	0
Magnesium			
Very high	7	4	5
High	60	73	78
Medium	30	22	16
Low	3	1	1
Very low	0	0	0
Phosphorus			
High	5	2	3
Medium	7	4	4
Low	16	19	22
Very low	72	75	71
Potassium			
Very high	10	12	16
High	15	18	35
Medium	25	36	41
Low	23	24	12
Very low	27	10	6
Active Organic Matter			
High	34	15	17
Medium	37	43	43
Low	29	42	40

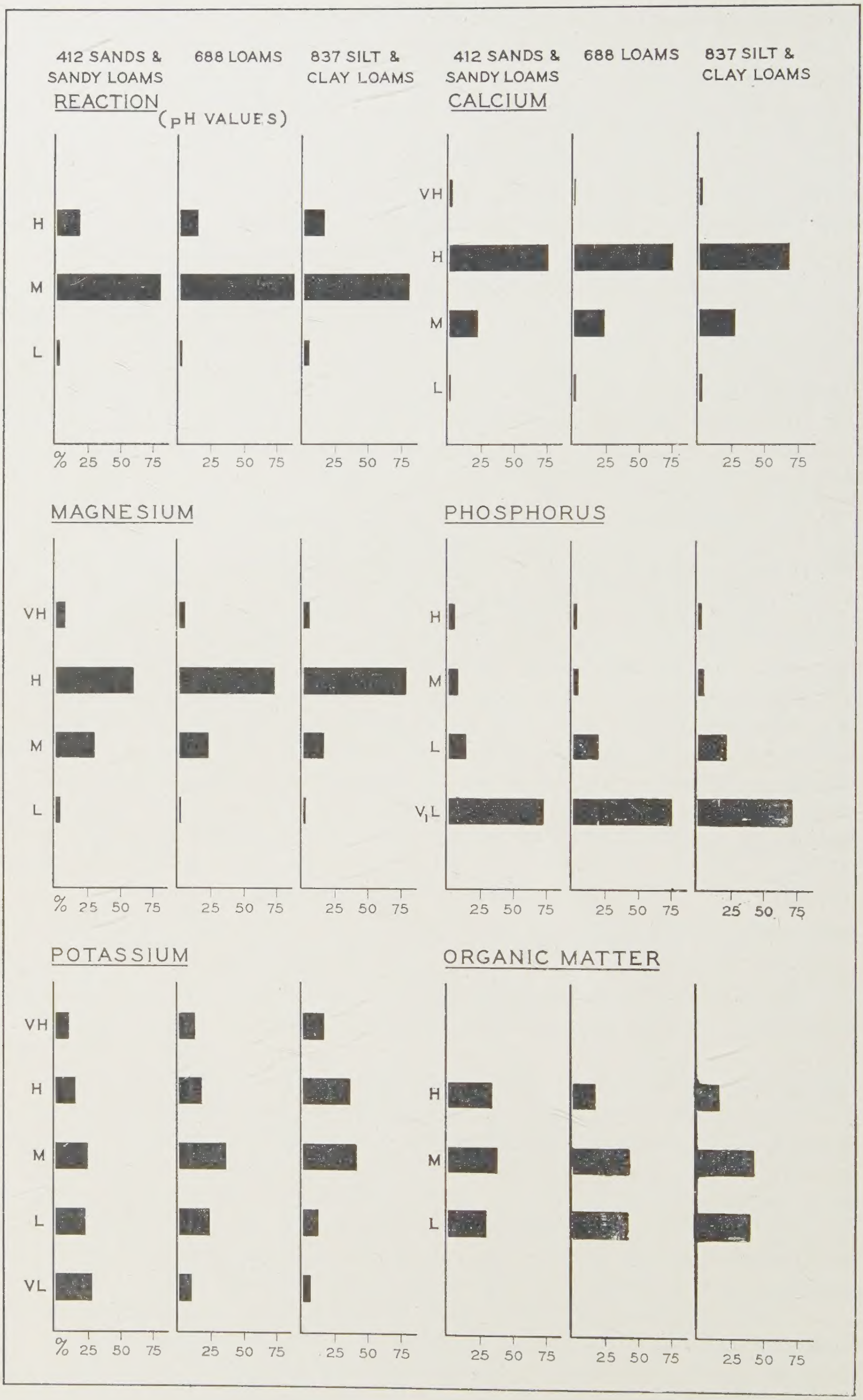

Figure 1. Fertility ratings by soil textural groups.

Reaction, Calcium and Magnesium

Only a very few samples were below a medium rating in reaction and still fewer were low in water soluble calcium and magnesium. This indicates that there is very little need for the addition of lime to the soils of York County.

A glance at Figure 1 will indicate that there is no appreciable difference in the three textural groups in this respect. Most of the few acid samples came from the southern and central western parts of the county, where the soils contain a larger proportion of shale.

In the farmers' answers to the questionnaires only a few indicated difficulty in getting satisfactory catches of clover, and most of these were in poorly drained areas.

Phosphorus

More than 90% of all samples sent in were below medium in phosphorus content. Again the distribution into the various classes or ratings was similar for all three textural groups, the largest percentage in each case falling into the very low class.

From these data it appears that there is a fairly general need for phosphates in York County soils. This agrees with previous findings which indicate that a low phosphate condition is general throughout southwestern Ontario (4).

Potassium

The levels of potassium were much more variable throughout the county than were those of the previously mentioned constituents. The western and southern parts of the county appear to be much better supplied with potassium than the eastern, central, and northern sections. Also, the heavier soils contain larger amounts than the lighter soils. In the silt and clay loam groups only 18% of the samples fall in the low and very low classes, while in the sandy group 50% are thus rated. It appears, therefore, that there is considerable need for added potash in York County soils, more particularly in those of lighter texture.

Active Organic Matter

The total organic matter content of the soil in any given region usually bears some relationship to topography and drainage. The active organic matter content is usually proportional to the total but varies with soil management. As indicated in the appendix, the samples have been divided into three arbitrary groups according to active organic matter content—low, medium, and high. There are not sufficient data at the moment to say just what is an optimum level, but the fact that 30 to 40% of all samples were given a low rating suggests that more attention should be paid to this vital constituent. In some cases, barnyard manure could be handled with less waste, but as the most effective means of increasing organic matter content, the plowing down of green manuring crops is of chief importance. It has been pointed out that phosphates, and in some instances potash, are lacking in this area, but fertilizers supplying these elements can be used most economically only when the active organic matter content is sufficiently high to provide optimum physical and microbiological conditions.

About 4% of all samples came from gardens. These samples, in most cases, had higher levels of phosphorus, potassium and organic matter than the general average, but did not appreciably change the picture. They were mostly in the sandy and loam groups.

Fields which had been previously fertilized supplied 32% of all the samples. The average fertility level of these samples, however, was no higher than that of all samples. This is quite to be expected, keeping in mind the usual small amounts of fertilizer applied and the larger yields of crops obtained.

As stated at the outset, this survey was undertaken primarily to assist the farmer in solving his soil fertility problems. Because of the manner of distribution of recommendations—through the Agricultural Representative—it is felt that intelligent interpretations have been made possible, the information used most effectively, and the main purpose of the survey accomplished.

The Agricultural Representative has himself been assisted by the knowledge gained of the outstanding soil deficiencies of the various regions of his county, for he can plan soil improvement programs along lines best suited to the conditions revealed by the project.

Finally, additional information has become available to our soil workers, which will lead to improvement in the technique and methods of analysis, an important consideration in view of the increasing use of chemical methods for determining soil deficiencies and for assisting in the conservation of our soil resources.

APPENDIX

Following is a brief description of the analytical procedures employed in the present survey. The limits and ranges of the ratings used for each constituent are based on the experiences of various soil workers, and in the light of present information appear to be reliable for Ontario conditions.

1. *Texture:* by fieldmen's method (inspection and feel). The samples were divided into three groups—coarse, medium and fine texture. They have been designated as (1) sands and sandy loams, (2) loams and (3) silt and clay loams. (The few organic soils which were sent in are not included in this discussion.)

2. *Reaction*: the colorimetric method using bromthymol blue indicator (Reacto-soil).

The grouping is as follows:

L	—	pH 5.6 – 6.0
M	—	pH 6.2 – 7.2
H	—	pH 7.4+

In view of the fact that in this part of Ontario the zone of leaching is comparatively shallow, with carbonates occurring frequently within the plow soil and abundantly in the parent soil material, it is considered that soils of pH 6.2 or higher are usually in no immediate need of lime. The exception to this may be in those cases where the supply of active calcium and magnesium is definitely low.

3. *Water soluble Calcium*: by the Method of Spurway (6). The limits* of the ratings are expressed as pounds per acre of Ca, as follows:

VL	—	0 – 300 lb. per acre six inches
L	—	320 – 600 lb. per acre six inches
M	—	700 – 1000 lb. per acre six inches
H	—	1100 – 1400 lb. per acre six inches
VH	—	1500+ lb. per acre six inches

* The limits of the ratings are expressed differently for purposes of uniformity.

4. *Water soluble Magnesium:* by the Method of Spurway (6). The limits* are expressed as pounds per acre of Mg.

VL	—	0 – 6	lb. per acre six inches
L	—	8 – 20	lb. per acre six inches
M	—	30 – 45	lb. per acre six inches
H	—	50 – 60	lb. per acre six inches
VH	—	60+	lb. per acre six inches

5. *Dilute acid-soluble Phosphorus:* by the Modified Thornton Method (5). The limits* are expressed as pounds per acre of P_2O_5.

VL	—	0 – 25	lb. per acre six inches
L	—	30 – 60	lb. per acre six inches
M	—	60 – 110	lb. per acre six inches
H	—	120+	lb. per acre six inches

6. *Replaceable Potassium:* by the Method of Thornton (8). The limits* are expressed as pounds per acre of K_2O.

VL	—	0 – 50	lb. per acre six inches
L	—	80 – 120	lb. per acre six inches
M	—	160 – 260	lb. per acre six inches
H	—	320 – 450	lb. per acre six inches
VH	—	500+	lb. per acre six inches

These values are in accordance with those established by Bell and Thornton (2).

7. *Active Organic Matter:* By the rapid chromic acid digestion method of Thomas (7).

Since the optimum organic matter content of a soil depends to a large degree upon the texture, it was necessary to use lower limit values for the sandy soils than for the loams. In deciding upon these ranges, the classification of Hester (3), worked out for coastal plain soils, was used as a guide, taking into consideration the fact that organic matter is more easily retained in soils of the higher latitudes. The following values assigned must, therefore, be considered as arbitrary.

Sandy Soils		*Loam and Clay Loam Soils*	
0 – 2.0%	Low	0 – 2.5%	Low
2.05% – 3.0%	Medium	2.55% – 3.5%	Medium
3.05%+	High	3.55%+	High

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*The limits of the ratings are expressed differently for purposes of uniformity.

THE USE OF THE WILTING COEFFICIENT IN SOIL MOISTURE STUDIES IN SOUTHWESTERN SASKATCHEWAN[1]

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One of the fundamental concepts in soil moisture studies is that of "available moisture". By this is meant the "moisture available for plant growth", as defined by Briggs and Shantz (3). It is the difference between the current moisture content of the soil when sampled and the moisture content of the same soil at the permanent wilting point of plants. The maximum available moisture or the available moisture capacity of a soil is obtained by finding the difference between the field capacity and the permanent wilting percentage.

THE MOISTURE EQUIVALENT METHOD FOR DETERMINING THE PERMANENT WILTING PERCENTAGE

As the wilting percentage varies widely with soil texture, a great many determinations of wilting points are usually necessary in each experiment. The direct method of actually growing plants in the soil under restricted moisture conditions is naturally a slow and tedious process. To facilitate the work, Briggs and Shantz (3) developed an indirect method by which they used the centrifuge to find the "moisture equivalent", and then divided by 1.84 to obtain the "wilting coefficient". The factor 1.84 was so chosen that the wilting coefficient approximated the directly determined permanent wilting percentage.

The Briggs and Shantz method as outlined was used in the laboratory at Swift Current from 1929 to 1934. Then it was decided that the ratio 1.84 was too low and the value 2.71, as given by Briggs and Shantz for the ratio of moisture equivalent to hydroscopic coefficient, was substituted. This ratio has been used at Swift Current since 1934. The hygroscopic moisture, as calculated from the moisture equivalent, has been used by Ellis and Shafer (4) in determining the total quantity of water available for the wheat crop.

Since Briggs and Shantz published their results, Veihmeyer and Hendrickson (8), Work and Lewis (9) and others have shown that no single ratio common to all soils exists between the moisture equivalent and the permanent wilting percentage. In a series of trials with 100 soils Veihmeyer and Hendrickson found the ratio ranged from 1.39 to 3.82. No definite dependence on texture was found.

In view of these results it became necessary to obtain more basic information on the soils in southern Saskatchewan. Table 1 contains soil moisture data relating to soils from various locations (mostly experimental sub-stations) in the area. In each case the determinations were made on composite samples taken from 8 to 12 borings in specially selected

[1] Contribution from the Experimental Farms Service (P.F.R.A.), Dominion Department of Agriculture, Ottawa, Canada. Read to the Soils Group of the Canadian Society of Technical Agriculturists at the Twentieth Annual Meeting at Winnipeg, Man., June 19 to 22, 1940.

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TABLE 1.—SOIL MOISTURE DATA ON SOILS FROM EXPERIMENTAL SUB-STATIONS

Location of sub-station	Depth	Permanent wilting percentage	Moisture equivalent	$\frac{ME}{PWP}$	Normal moisture capacity	$\frac{NMC}{PWP}$	Available moisture capacity	Mechanical analysis			Soil moisture content at seeding time 1938	Soil moisture content at harvest time 1938
								Sand	Silt	Clay		
	in.	%	%		%		%	%	%	%	%	%
Piapot	0–6	4.79	9.60	2.00	13.46	2.81	8.67	78.5	13.2	8.3	11.60	3.27
	6–12	4.89	10.55	2.16	13.16	2.69	8.27	77.2	13.5	9.3		
	12–24	4.72	9.84	2.09	13.07	2.77	8.35	79.6	10.4	10.0	8.85	2.89
	24–36	3.24	6.65	2.05	10.11	3.12	6.87	86.7	5.4	7.9	6.85	2.70
	36–48	3.39	5.65	1.67	10.28	3.03	6.89	87.0	5.0	8.0	2.59	2.26
Valjean	0–6	5.63	11.92	2.12	16.24	2.88	10.61	76.3	12.6	11.1	14.89	3.91
	6–12	5.94	12.93	2.18	17.64	2.97	11.70	73.7	13.7	12.6		
	12–24	4.97	10.29	2.07	12.39	2.49	7.42	77.9	11.1	11.0	10.00	3.80
	24–36	5.53	12.51	2.26	14.70	2.67	9.17	70.4	13.7	15.9	7.74	7.33
	36–48	5.05	11.59	2.29	13.96	2.76	8.91	70.2	14.5	15.3	5.84	–
Herbert	0–6	6.78	16.12	2.38	18.09	2.67	11.31	58.6	23.2	18.2	14.54	5.50
	6–12	6.95	14.29	2.06	16.60	2.39	9.65	59.6	16.6	23.8		
	12–24	9.11	19.53	2.14	20.47	2.25	11.36	43.5	25.7	30.8	11.24	7.66
	24–36	8.47	20.18	2.38	20.63	2.44	12.16	41.5	27.3	31.2	7.06	–
	36–48	5.72	12.15	2.12	14.85	2.60	9.13	62.7	15.9	21.4	4.87	–
Shaunavon	0–6	9.86	21.66	2.20	23.71	2.40	13.85	35.1	33.9	31.0	17.05	6.57
	6–12	10.56	22.08	2.09	22.83	2.16	12.27	36.4	29.4	34.2		
	12–24	9.55	20.58	2.15	20.50	2.15	10.95	37.5	21.5	41.0	13.41	7.56
	24–36	10.21	21.40	2.09	20.54	2.01	10.33	36.0	22.5	41.5	12.54	5.82
	36–48	10.50	22.02	2.10	20.48	1.95	9.98	36.1	22.3	41.6	12.17	7.44
Kincaid	0–6	10.83	23.49	2.17	23.85	2.20	13.02	28.4	41.2	30.4	19.48	7.62
	6–12	10.72	22.44	2.09	23.23	2.17	12.51	27.5	41.8	30.7		
	12–24	10.17	21.89	2.15	22.94	2.25	12.77	32.4	40.7	26.9	14.74	7.85
Riverhurst	0–6	10.26	24.09	2.35	24.08	2.35	13.82	23.0	50.7	26.3	22.58	8.40
	6–12	11.27	24.47	2.17	23.82	2.11	12.55	25.2	42.2	32.6		
	12–24	11.41	25.65	2.25	23.80	2.09	12.39	16.5	44.3	39.2	14.66	9.29
	24–36	10.11	26.11	2.58	24.17	2.38	14.06	10.0	51.5	38.5	9.17	9.27
	36–48	9.70	25.06	2.58	22.15	2.28	12.45	10.0	57.8	32.2	9.39	–
Carmichael	0–6	10.71	28.01	2.61	32.15	3.00	21.44	26.0	48.0	26.0	24.65	7.98
	6–12	10.94	25.26	2.31	27.58	2.52	16.64	21.5	47.4	31.1		
	12–24	10.08	23.27	2.31	24.35	2.41	14.27	19.8	50.7	29.5	13.00	8.37
	24–36	8.48	20.90	2.47	21.15	2.49	12.67	23.6	46.8	29.6	9.07	7.83
	36–48	8.64	21.22	2.46	20.54	2.38	11.90	29.2	36.3	34.5	9.91	–
Canuck	0–6	11.11	22.88	2.06	25.47	2.29	14.36	36.1	28.3	35.6	17.37	7.12
	6–12	11.90	24.40	2.05	26.50	2.23	14.60	31.0	28.8	40.2		
	12–24	11.22	24.63	2.20	24.65	2.20	13.43	34.4	23.0	42.6	10.88	8.77
	24–36	10.78	24.87	2.30	24.17	2.24	13.39	32.8	23.6	43.6	9.49	9.48
	36–48	10.83	22.43	2.07	22.16	2.05	11.33	35.3	24.6	40.1	10.16	9.25
Fox Valley	0–6	11.19	23.19	2.07	24.09	2.15	12.90	30.8	34.5	34.7	16.23	8.07
	6–12	11.32	24.50	2.16	26.30	2.32	14.98	28.8	36.2	35.0		
	12–24	12.70	24.96	1.97	26.90	2.12	14.20	14.5	42.1	43.4	17.17	6.58
	24–36	11.76	21.47	1.83	25.05	2.13	13.29	16.5	42.0	41.5	12.69	5.22
	36–48	10.87	21.46	1.97	23.55	2.17	12.68	18.0	40.0	42.0	9.29	5.07
Limerick	0–6	11.96	27.18	2.27	27.80	2.32	15.84	25.5	36.6	37.9	23.58	11.74
	6–12	12.32	25.88	2.10	26.42	2.14	14.10	22.8	37.4	39.8		
	12–24	13.76	25.34	1.84	27.12	1.97	13.36	22.8	31.3	45.9	21.71	10.38
	24–36	13.55	27.19	2.01	28.75	2.12	15.20	21.1	27.5	51.4	17.57	10.69
	36–48	13.14	26.72	2.03	31.61	2.41	18.47	23.6	28.1	47.3	15.21	10.94

TABLE 1.—SOIL MOISTURE DATA ON SOILS FROM EXPERIMENTAL SUB-STATIONS—*Con.*

Location of sub-station	Depth	Permanent wilting percentage	Moisture equivalent	$\frac{ME}{PWP}$	Normal moisture capacity	$\frac{NMC}{PWP}$	Available moisture capacity	Mechanical analysis: Sand	Silt	Clay	Soil moisture content at seeding time 1938	Soil moisture content at harvest time 1938
	in.	%	%		%		%	%	%	%	%	%
Gravel-bourg	0– 6	13.26	27.96	2.11	29.80	2.25	16.54	23.5	37.8	38.7	24.63	7.13
	6–12	13.06	26.81	2.05	29.25	2.24	16.19	22.6	38.2	39.2		
	12–24	12.43	26.18	2.11	28.45	2.29	16.02	22.9	32.5	44.6	22.64	9.58
	24–36	12.36	24.52	1.98	27.47	2.22	15.11	22.2	33.3	44.5	18.10	13.20
	36–48	14.48	26.90	1.86	31.91	2.20	17.43	18.5	32.3	49.2	19.00	19.19
Sceptre*	0– 6	19.69	36.70	1.86	35.37	1.80	15.68	16.6	28.2	55.2	28.27	24.27
	6–12	19.90	37.42	1.88	36.67	1.84	16.77	16.7	23.5	59.8		
	12–24	19.37	37.63	1.94	36.10	1.86	16.73	15.6	21.2	63.2	23.03	19.91
	24–36	20.00	37.40	1.87	37.76	1.89	17.76	–	–	–	20.90	21.70
	36–48	21.39	36.74	1.72	38.37	1.80	16.98	–	–	–	23.67	24.39

*Special area, not an Experimental Sub-station.

areas. The permanent wilting percentage was obtained by the method outlined by Work and Lewis (9). The normal moisture capacity was determined by a modification of the method of Olmstead (5). Mechanical analysis was carried out by the Bouyoucos method (1).

In comparing columns 4 and 6 of Table 1, it appears that the moisture equivalent gives a good approximation to the normal moisture capacity for all except sandy soils in which case the moisture equivalent is lower. This observation is in agreement with reports by Olmstead (5), Veihmeyer (7), and Piper (6).

The ratio moisture equivalent to permanent wilting percentage, Table 1, column 5, varies from 1.67 to 2.61. The highest values were obtained for medium textured soils, the ratios falling off for sands and clays. No simple relation between the ratios and soil texture can be obtained for these data. It is notable, however, that the ratio normal moisture capacity to wilting percentage changes fairly uniformly from the lowest value 1.80 for a fine textured soil to the highest value 3.12 for a coarse sandy soil. For the top 6-inch layer particularly, the data give a good linear relationship when the ratios are plotted against normal moisture capacities.

INTERPRETATION OF READILY AVAILABLE MOISTURE

A comparison of columns 3 and 13, Table 1 shows that the soil moisture content at harvest time is often below the permanent wilting percentage. This condition is found even at the lower depths where surface evaporation is not a factor. It must be concluded that the permanent wilting percentage is not the minimum of moisture left by plant roots in the soil. Also the available moisture is not the maximum quantity of moisture removable by plants.

The above conclusions are in general agreement with those of Briggs and Shantz (3). These authors found that there was a loss of moisture through the plant after wilting; in fact, the loss continued even after the

TABLE 2.—WATER REQUIREMENTS OF WHEAT GROWN IN THE GREENHOUSE UNDER CONTROLLED MOISTURE CONDITIONS

Sub-station	Permanent wilting percentage	Treatment number	Soil moisture content at harvest time	Amount of water used	Yield of grain	Water requirement
	%		%	gms.	gms.	gms. of water per gm. of grain
Valjean	5.83	1	3.70	777	0.275	2825
		2	3.91	1264	0.675	1873
		3	4.01	1679	1.200	1400
		4	4.23	2711	2.580	1051
		5	5.09	3202	3.900	821
Herbert	6.30	1	4.74	856	0.350	2446
		2	4.76	1348	0.750	1798
		3	4.70	1734	1.030	1683
		4	4.71	2627	2.600	1010
		5	5.92	3219	4.050	795
Swift Current	9.91	1	6.33	851	0.450	1892
		2	6.47	1361	0.830	1640
		3	6.52	1821	1.250	1456
		4	7.34	2827	3.000	942
		5	9.08	3188	3.500	910
Carmichael	10.65	1	7.06	966	0.300	3220
		2	7.29	1461	0.530	2757
		3	7.61	2141	0.980	2185
		4	7.71	3470	2.430	1428
		5	8.22	4081	3.980	1025
Tugaske	9.60	1	6.54	1038	0.380	2731
		2	6.49	1547	0.600	2580
		3	6.53	2236	1.200	1863
		4	7.13	3634	3.630	1001
		5	7.35	4085	4.450	918
Tompkins	9.52	1	6.26	1053	0.130	8100
		2	6.63	1442	0.330	4370
		3	6.79	2172	1.100	1975
		4	7.21	3491	3.400	1027
		5	7.70	3874	4.530	855
Gravelbourg	10.00	1	7.37	1231	0.280	4395
		2	7.50	1744	0.500	3488
		3	7.60	2926	1.900	1540
		4	8.00	4057	2.930	1384
		5	8.88	5295	5.750	921
Shackleton	15.28	1	11.24	959	0.625	1535
		2	11.65	1442	1.180	1222
		3	11.66	1960	1.630	1202
		4	13.55	2428	2.600	934
		5	13.91	3145	3.550	886
Sceptre*	22.31	1	18.52	1458	1.050	1389
		2	18.84	1944	1.650	1178
		3	19.58	2501	2.330	1074
		4	23.17	3228	3.200	1009
		5	30.60	3594	3.400	1057

*Special area, not an Experimental Sub-station.

subsequent drying and death of the plant. The wilting point indicated merely the cessation of growth. Briggs and Shantz noted also that the plant may draw its moisture from the lower depths in the soil and that "the upper soil mass is usually reduced below the wilting coefficient long before wilting actually takes place". This observation emphasizes the fact that the wilting point depends not only on the forces holding the soil moisture but also on the rate at which the moisture is supplied to the plant.

Because of the uncertainty of the wilting point of wheat, it was impossible to check the observation that the soil in the upper layer falls below the permanent wilting percentage before the plant wilts. Certain it is, however, that the soil moisture is normally reduced to below the wilting percentage at harvest time. This condition exists whether or not moisture may be brought up from lower depths.

Results of a series of greenhouse experiments are presented in Table 2. Twenty 1-gallon crocks were filled with soil, seeded to wheat, and sealed to prevent direct evaporation from the surface. During the initial stages of growth the soil moisture content was maintained near the field capacity. Then the moisture was cut off at 5 different stages of growth and the crop was allowed to mature. Some grain was produced in each case, although the yield and quality of the grain that had the moisture cut off the earliest were low. The percentage moisture at harvest was obtained by taking representative samples from each crock and drying at 105° C. The data given in Table 2 represent the average of 4 replicates. Wilting percentage determinations were obtained by the direct method, using sunflowers as indicators.

The data in Table 2, column 4 show that in the first three treatments the final minimum moisture content was nearly constant. In the fourth and fifth, the demand for water was reduced and a greater supply remained in the soil. The water requirement, expressed as grams of water per gram of grain, is given in column 7. The growth was so poor in the first three treatments of each set that the ratio was naturally very high and undependable. However, the relative variation within each set was as would be expected, viz., the efficiency in moisture use increased with increase in water supply as normal growth conditions were approached. The fifth treatment was maintained under optimum conditions for most of the period. After a certain stage the lowering of the soil moisture to the wilting point does not seem to have a very detrimental effect on the wheat crop. The fine textured soils from Sceptre and Shackleton were particularly efficient in the use of water under low moisture conditions.

An attempt was made to obtain wilting point data from the crocks, using the wheat as indicator plant. This failed since no definite wilting point of wheat could be established. From observation the wilting percentage would be slightly higher than the minimum reached by the soil at harvest. Though the wilting point is not always sharply defined, it exists undoubtedly as a point or region where the development of the plant is strongly modified by lack of moisture. This point often comes early in the case of wheat growing in the drier districts. However, even if vegetative growth stops near the wilting point, it does not mean that any further reduction of moisture is a total loss. This might be the case if

TABLE 3.—USE OF SOIL MOISTURE AT THE EXPERIMENTAL SUB-STATIONS IN SOUTHWESTERN SASKATCHEWAN

Location of sub-station	Moisture equivalent	Permanent wilting percentage†	Soil moisture content at seeding time	Soil moisture content at harvest time	Seasonal rainfall	Total water used	Yield of grain**	Water requirement
	%	%	%	%	in.	in.	bu. per acre	lbs. of water per lb. of grain
1938								
Valjean	11.70	5.33	9.62	5.22	4.21	7.53	6.0	4745
Herbert	16.77	7.54	9.43	5.92	2.81	5.34	Failure	—
Shaunavon	21.47	10.12	13.79	6.85	4.38	9.24	7.0	4990
Kincaid	22.43	10.47	17.11	7.73	10.92	17.64	23.0	2898
Riverhurst	25.30	10.50	13.95	9.07	4.17	7.00	6.5	4070
Carmichael	23.03	9.50	14.16	8.00	7.52	11.51	10.0	4352
Canuck	23.89	11.08	11.97	8.65	6.00	8.32	7.0	4491
Limerick	26.45	13.15	19.52	10.94	9.92	15.69	8.7‡	6813
Gravelbourg	26.25	13.11	21.09	12.27	7.29	13.05	18.0	2740
1939								
Valjean	17.28	7.93	13.63	6.29	7.20	12.74	20.0	2409
Herbert	19.28	8.44	8.90	6.02	8.42	10.49	18.7	2120
Swift Current	22.01	8.60	17.59	8.00	7.23	13.52	31.8	1607
Carmichael	22.14	9.20	10.47	8.75	15.54	16.66	41.2	1528
Tugaske	23.91	10.39	15.79	10.40	10.91	14.53	30.7	1790
Tompkins	25.74	11.27	12.64	12.16	12.71	13.02	37.9	1299
Gravelbourg	29.21	14.60	15.42	11.20	9.51	12.27	25.0	1856
Shackleton §	32.01	15.99	23.19	15.33	2.19	7.38	35.7	781
Sceptre*	41.44	22.45	27.54	21.77	9.73	13.25	34.8	1440

†Data for 1939 calculated from direct determinations made in 1938.
**1938 yields are those of the whole strip. 1939 yields are from small sample areas except at Valjean and Gravelbourg where they are the average of the whole strip.
‡Rust damage.
§Sampled late after spring rains.
*Special area, not a Sub-station.

we were interested in the total dry matter only. In wheat growing the important item is the grain, the yield and quality of which would be reduced were it not for the moisture "used" in excess of the "available moisture".

THE SIGNIFICANCE OF WILTING POINT DATA IN FIELD EXPERIMENTS

Moisture and yield data obtained at Sub-stations in 1938 and 1939 are given in Table 3. In each case the soil moisture data are based on samples obtained from 6 holes, each 4 feet in depth. The water requirements given in column 9 furnish a good measure of the moisture situation. The water requirements of crops were much greater in the dry season of 1938 than in the relatively wet season of 1939. Columns 3 and 4 of Table 3 show that the soil moisture contents of many fields in the spring of 1939 were only a few per cent above the wilting percentage. However, with heavy spring rains and cool weather, a very heavy stand was produced in all districts. Then, later, the hot dry weather rushed the grain to maturity, with the result that all crops produced far more straw than the yield of grain would indicate. In this respect the crops at Valjean, Herbert,

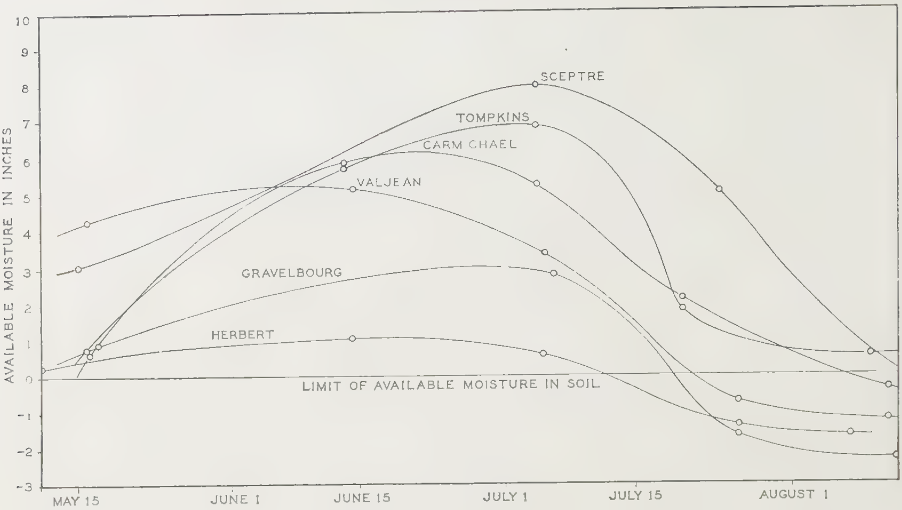

FIGURE 1. Available moisture under fallow crops on sub-stations throughout the season 1939.

and Gravelbourg suffered worse than the others. At these stations the soil moisture dropped below the wilting point at a relatively early stage of growth.

The use of moisture in different districts in 1939 is brought out more clearly in Figure 1. Actually the minimum moisture obtained at harvest is higher than it should be. In most cases the dry weather brought the crops to maturity before all the available moisture had been removed from the fourth foot of soil.

When the moisture and root distributions are uniform, the field minimum at harvest may be considered constant year after year.

One of the important uses of the available moisture determination is suggested by Figure 1 where the use of soil moisture by crops is followed throughout the season. Assuming normal weather conditions, the prospects of an average crop may be judged from the condition of the crop and the amount of moisture readily available. In soil moisture studies of all kinds the readily available moisture is usually the most important determination. It has greater practical value than the water holding capacity since, on most soils, treatments which increase the water holding capacity also increase the wilting percentage, so that the net benefit to the crop is smaller than might be expected. This point is stressed in studying the effect of applying manure or growing grasses to increase the organic matter content of the soil.

In some experiments available moisture, based on the minimum soil moisture content in the field at harvest time, may be useful. This would depend on the nature of the experiment, the uniformity of the soil, and the number of replicates used in sampling. It must be emphasized, however, that all the moisture above the field minimum is not readily available for crop growth and that in the growth of forage crops or fruits and vegetables some of the moisture thus termed available would be of no value.

From the foregoing it appears that the readily available moisture based on directly determined wilting percentages supplies a satisfactory basis for soil moisture studies in Southern Saskatchewan. However, the direct determination on all samples coming to the Laboratory would be impossible. There remains still the problem of deciding upon a satisfactory indirect method. The Bouyoucos Dilatometer method (2) was tested at this Laboratory and found to give results varying from 1.03% below to 4.56% above the directly determined wilting percentage. The method would not prove satisfactory for our routine work. In many ways the moisture equivalent method is still the quickest and most accurate. The procedure now used at Swift Current depends on the nature of each particular experiment. Three familiar situations are discussed.

(1) In many projects the moisture condition is followed year after year on uniform strips or plots. In such cases the difference between spring and harvest sampling is all that is required to check moisture use. A minimum of 4 holes per plot, taken with successive holes within a few feet of each other, gives satisfactory results.

(2) When the location of sampling on each strip is changing continually, or when the soil texture varies through short distances, a direct wilting point determination is advisable at first. Then if the moisture equivalent does not change markedly with successive borings, the wilting percentage can be calculated by using the ratio $\frac{ME}{PWP}$ initially determined. Where the soil texture is very variable, more direct determinations may be necessary.

(3) Accurate values for available moisture cannot be given for small samples coming in from country points. When an approximate value is required, the moisture equivalent and average ratios for wilting percentage or hygroscopic moisture are used as in the past. The ratios can be improved upon as we gain more information about the soils in the different districts.

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PASTURE STUDIES

XVIII. THE AVAILABILITY, UTILIZATION AND FIXATION OF POTASSIUM APPLIED TO PERMANENT PASTURES[1]

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INTRODUCTION

The relative importance of potassium in the improvement of Quebec permanent pastures by fertilization may be judged from the recommendations of the Provincial Pasture Committee. The application of 400 to 500 pounds of 20% superphosphate and 75 to 100 pounds of muriate of potash per acre, or the equivalent, every two, three, or four years, depending on the situation, is recommended for pastures on medium to light textured soils where wild white clover is present in the sward. This recommendation is being adopted to an increasing extent in the Eastern Townships of Quebec, where it is applicable to large areas.

The main basis for recommending the application of potash appears to be that, particularly in combination with phosphate, it is effective in improving the botanical composition of the sward. It is considered that the application of potash alone rarely produces worthwhile improvements. The effect of potassium on yield of herbage is usually small.

The investigation reported here was undertaken as part of the general research program of the Macdonald College Pasture Committee. Wrenshall and McKibbin (12) have dealt with the effects on the soil of surface applications of superphosphate, but hitherto no information has been obtained with regard to the fate of potassium applied to the surface of Quebec permanent pastures. The present investigation was intended to throw light on the penetration, the fixation in available and unavailable forms, and the utilization by the plants of potassium applied as muriate of potash.

EXPERIMENTAL MATERIAL AND METHODS

A series of pasture plots in the neighbourhood of North Hatley, Stanstead County, Que., was selected for this study. The dominant soil type here is classed as Hatley Sandy Loam, a podsolic soil, differing only in minor respects from most of the upland soils found throughout the Eastern Townships region.

The plots had been laid down in the fall of 1935. In the fall of 1937 they were subdivided and part of each plot was refertilized with the same treatment that it received originally. Soil samples were taken from the once fertilized areas, and also from the refertilized areas, in the fall of 1938. Samples were taken at two depths, namely 0″–1″, and 1″–3″. The plots sampled on each farm had received the following treatments.

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Fertilizer Treatment	*Abbreviated Designation*
1. No treatment	Nil
2. 100 lb. KCl per acre	K
3. Same as 2, refertilized	KR
4. 200 lb. KCl per acre	2K
5. Same as 4, refertilized	2KR
6. 100 lb. KCl, and 700 lb. superphosphate per acre	K3P
7. Same as 6, refertilized	K3PR
8. 200 lb. KCl, and 700 lb. superphosphate per acre	2K3P
9. Same as 8, refertilized	2K3PR
10. 100 lb. KCl, and 2 tons $CaCO_3$ per acre	KCa
11. Same as 10, refertilized	KCaR
12. 100 lb. KCl, 700 lb. superphosphate and 2 tons $CaCO_3$ per acre	K3PCa
13. Same as 12, refertilized	K3PCaR

The soil samples were air-dried, pulverized, and screened through a 2-mm. sieve. They were analyzed for available (exchangeable) potash by the method of Truog and Volk (9). The capacities of some of the samples to fix potassium in unavailable form were estimated by the method of Volk (11).

Samples of the herbage clipped from the plots were on hand. Suitable composites were analyzed for potash by an adaptation of the Truog and Volk method. These results were combined with yield data to give figures for the removal of potash by the herbage.

Botanical readings on the swards of the plots had been recorded, and these data were treated statistically to determine the effects of potash treatments.

DATA AND DISCUSSION

Effect of Potash on Botanical Composition and Yield

The results of the statistical study of botanical data, which will not be presented in detail here, confirm the general opinion that potassium is beneficial in improving the sward. The significant conclusions are as follows:

> Potassium increased the clover in the sward, this action being most pronounced when phosphate also was applied.
>
> Potassium stimulated the useful grasses. The application of 200 pounds of muriate of potash alone caused a significant increase in the proportion of grass in the sward.
>
> Potassium fertilization caused a highly significant decrease in the proportion of bare ground and moss.

Frankton (2) has analyzed the yield data for these plots, and found that the effect of potash was not significant. Previously Nowosad (6) observed a small, but statistically significant, increase in yield due to application of potash to pastures in the Cowansville district.

TABLE 1.—AVAILABLE K_2O IN THE SOIL OF PASTURE PLOTS

Treatment and depth of layer (inches)	McClary		Pope		McVittie	
	1*	2†	1	2	1	2
Nil, 0–1	150	43	402	115	154	44
Nil, 1–3	64	37	207	118	43	25
K, 0–1	218	62	376	108	184	53
K, 1–3	90	51	180	103	43	25
KR, 0–1	227	65	406	116	231	66
KR, 1–3	94	54	214	122	66	38
2K, 0–1	160	46	389	111	400	114
2K, 1–3	92	53	175	100	150	86
2KR, 0–1	244	70	462	132	438	125
2KR, 0–3	105	60	197	113	156	89
K3P, 0–1	152	43	244	70	220	63
K3P, 1–3	92	53	115	66	77	44
K3PR, 0–1	180	51	278	79	227	65
K3PR, 1–3	81	47	122	70	81	47
2K3P, 0–1	184	53	274	78	319	91
2K3P, 1–3	83	48	100	57	79	45
2K3PR, 0–1	197	56	336	96	321	92
2K3PR, 1–3	70	40	130	75	85	49
KCa, 0–1	182	52	364	104	274	78
KCa, 1–3	92	53	207	119	102	59
KCaR, 0–1	177	51	391	112	297	85
KCaR, 1–3	98	56	250	143	135	77
K3PCa, 0–1	152	43	248	71	259	74
K3PCa, 1–3	64	37	120	69	83	48
K3PCaR, 0–1	197	56	280	80	284	81
K3PCaR, 1–3	94	54	128	73	75	43

* Parts per million in sample.
† Pounds per acre in soil layer.

Available Potash in the Soils

The results for exchangeable potash in the soil samples from the pasture plots are recorded in Table I. The concentration of exchangeable potash (K_2O) is expressed as parts per million of the air-dried soil in column 1, and as pounds per acre in the corresponding soil layer in column 2, for each farm. The exchangeable potash, as determined, is considered to represent available potassium.

Considering the results, it is seen that the concentration of available potash is invariably higher in the 0″–1″ layer than in the 1″–3″ layer. Evidently the potassium which reaches the soil, whether in plant and animal residues, or applied as fertilizer, tends to accumulate at the surface. The level of available potash in the surface layer of unfertilized areas is probably about adequate for the type of crop being grown, but the lower layer must be classed as deficient, having only one-third to one-half the concentration of potash found in the surface layer. This situation is doubtless of considerable practical significance, for it is clear that the main action of the potash fertilizer is upon the layer which has little or no need of it. However, it may be seen that the applied potash has penetrated into the 1″–3″ layer to an appreciable extent. In this respect the retention of potash by the surface layer is considerably less efficient than was the retention of phosphate observed in the previous study by Wrenshall and McKibbin (12), where there was no appreciable penetration of phosphate beyond the surface one-half inch layer.

The increases in available potash due to the fertilizer treatments are given in Table 2, lending support to the above remarks. Special mention must be made of the results on the Pope plots, where there was generally less available potash in the fertilized plots than there was in the untreated plot. Additional samples were taken from this series, and it was established that the Nil plot does not represent truly the status of the untreated soil of this pasture, being abnormally rich in available potash. Making allowance for this exception, it is evident that, in general, potash treatments have increased the quantities of available potash in both layers. The level of available potash has been increased considerably more in the upper layer than in the lower, but the actual amount of the increase, expressed as pounds per acre, appears to be of the same order in both layers. It is unlikely that any appreciable amount of applied potash penetrated below the 3-inch depth. Analyses of samples representing the 3–6″ soil layer

Table 2.—Increases in available K_2O due to treatments

Treatment and depth of layer (inches)	McClary		Pope		McVittie	
	1*	2†	1	2	1	2
Nil, 0–1	–	–	–	–	–	–
Nil, 1–3	–	–	–	–	–	–
K, 0–1	68	19	− 26	− 7	30	9
K, 1–3	26	14	− 27	− 15	0	0
KR, 0–1	77	22	+ 4	+ 1	77	22
KR, 1–3	30	17	+ 7	+ 4	23	13
2K, 0–1	10	3	− 13	− 4	246	70
2K, 1–3	28	16	− 32	− 18	107	61
2KR, 0–1	94	27	+ 40	+ 17	284	81
2KR, 1–3	41	23	− 10	− 5	113	64
K3P, 0–1	2	0	−158	− 45	66	19
K3P, 0–3	28	16	− 92	− 52	34	19
K3PR, 0–1	30	8	−124	− 36	73	21
K3PR, 1–3	17	10	− 85	− 48	38	22
2K3P, 0–1	34	10	−128	− 37	165	47
2K3P, 1–3	19	11	−107	− 61	36	20
2K3PR, 0–1	47	13	− 66	− 19	167	48
2K3PR, 1–3	6	3	− 77	− 43	42	24
KCa, 0–1	32	9	− 38	− 11	120	34
KCa, 1–3	28	16	0	+ 1	59	34
KCaR, 0–1	27	8	− 11	− 3	143	41
KCaR, 1–3	34	19	+ 43	+ 25	92	52
K3PCa, 0–1	2	0	−154	− 44	105	30
K3PCa, 1–3	0	0	− 87	− 49	40	23
K3PCaR, 0–1	47	13	−122	− 35	130	37
K3PCaR, 1–3	30	17	− 79	− 45	32	18

* Parts per million in soil sample.
† Pounds per acre in soil layer.

of fertilized[1] and unfertilized areas of the Little pasture (in the same locality as the McVittie plots) gave the following results, indicating that the penetration below 3″ is insignificant:

Treatment and soil layer (inches)	Available K_2O, p.p.m. in soil
Nil, 3-6	52
PK, 3-6	54

[1] The fertilization of this area approximated the K3PR treatment.

The results in Table I were subjected to analysis of variance to determine the probable significance of the changes in available potash produced by fertilization. The conclusions follow:

A. In the 0″–1″ layer

1. Comparing individual treatments with Nil, only the 2KR treatment produced a significant increase in available potash. This increase was highly significant ($P<0.01$).

2. The level of available potash in all treated plots taken together was not significantly higher than that of the Nil plots.

3. Comparison of the refertilized plots with those once fertilized failed to show a significant difference; however, the odds of significance were about 14 to 1 ($P = 0.078$).

B. In the 1″–3″ layer

Comparing individual treatments with Nil, only the CaKR treatment caused a significant increase ($P<0.05$). Other comparisons failed to show significant differences.

The observed increases in available potash appear to be of doubtful statistical significance. It was felt that the above-noted discrepancy in the Pope results may have obscured the issue. A further analysis of variance, from which the Pope results were excluded, was carried out. The conclusions from this treatment of the data were as follows:

Comparing individual treatments with Nil, the 2KR treatment caused a highly significant increase in available potash, and the 2K treatment caused a significant increase. The level of available potash in all the fertilized plots considered collectively is significantly higher than that of the untreated plots.

The above conclusions apply with equal force to both the soil layers.

The Effect of Superphosphate on Available Potash

Tables 1 and 2 show, in general, a higher concentration of available potash where KCl was applied alone than where it was applied in combination with superphosphate. The increases in pounds per acre of available potash due to A, application of KCl alone, and B, application of KCl with superphosphate (as detailed in columns 2 of Table II) are set out in the following tabulation.

Farm	A	*vs.*	B
McClary	193		101
Pope	−15		−514
McVittie	481		328

Table 3 is designed to show in detail the effect of superphosphate on the level of available potash, by comparing plots receiving potash alone with corresponding plots which received phosphate and potash. The statistical comparison of these plots showed that the effect of superphosphate in lowering the content of available potash was significant in both the 0″–1″ and 1″–3″ soil layers.

A similar result was previously obtained by Wrenshall and McKibbin (12) who showed that the available phosphorus was lower where potash was applied together with superphosphate than where superphosphate

TABLE 3.—AVAILABLE POTASH CONTENT OF PLOTS TREATED WITH POTASH WITH AND WITHOUT SUPERPHOSPHATE

Treatment	Depth of layer (inches)	McClary		Pope		McVittie	
		1*	2†	1	2	1	2
K	0–1	218		376		184	
K3P	0–1	152	66	244	132	220	−36
KR	0–1	227		406		231	
K3PR	0–1	180	47	278	128	227	4
2K	0–1	160		389		400	
2K3P	0–1	184	−24	274	115	319	81
2KR	0–1	244		462		438	
2K3PR	0–1	180	64	278	184	227	211
K	1–3	90		180		43	
K3P	1–3	92	− 2	115	65	77	−34
KR	1–3	94		214		66	
K3PR	1–3	81	13	122	92	81	−15
2K	1–3	92		175		150	
2K3P	1–3	83	9	100	75	79	71
2KR	1–3	105		197		156	
2K3PR	1–3	70	35	130	67	85	71

* Available potash in sample—parts per million.
† Decrease in available potash with application of superphosphate—parts per million.

was applied alone. Results of this kind may be attributed in part to the increased removal of nutrients because of larger yields from areas receiving the combined treatments. It is also possible that phosphate and potash exert mutual influences on their fixation in unavailable forms, although this has never been clearly demonstrated. When phosphate is fixed, the base exchange capacity of the soil may be increased, as was shown by Prince and Toth (7). According to Truog and Jones (8) the fixation of potash in non-exchangeable form is accompanied by an equivalent decrease in base exchange capacity. Perhaps these phenomena are related to one another. Joffe and Kolodny (4) have reported that complexes of iron, aluminium, calcium and magnesium phosphates are able to fix potassium in non-exchangeable form.

In order to demonstrate the degree of potash removal by the growing plants the yields and potash contents of herbage samples clipped from certain plots on the McVittie and McClary farms are given in Table 4. The 2K3P plots lost the largest amounts of potash, due to increased yields as well as to the high percentage of potassium in the herbage. The residual available potash of a 2K3P plot would tend to be lower than that of the corresponding 2K plot on this account. However, the relative magnitudes of the observed differences indicate that there probably is also an interaction between phosphate and potash which promotes fixation in relatively insoluble forms. The significance of this last remark will be made clearer by reference to the potash balance sheet, Table 6.

Many conflicting reports appear in the literature regarding the effect of calcic treatments on potash availability. Since the influence of superphosphate might possibly be due to its content of calcium, it is of interest to note in passing that the data show no indication of any interaction between lime and potash when these are applied in combination. Liming

TABLE 4.—THE UPTAKE OF POTASH BY THE HERBAGE

Treatment	Year	Yields from plots lb./ac.		K_2O in herbage %		K_2O removed by herbage lb./ac.	
		McVittie	McClary	McVittie	McClary	McVittie	McClary
Nil	1936	1580	832	1.08	1.30	17.1	10.8
	1937	1370	768	1.07	1.16	14.7	8.9
	1938	598	278	1.20	0.95	7.2	2.6
2K	1936	1196	608	2.16	2.00	25.8	12.2
	1937	1260	780	1.65	1.97	20.8	15.4
	1938	512	501	1.93	1.91	9.9	9.6
2K3P	1936	2295	780	2.13	1.87	48.9	14.6
	1937	1975	715	1.76	2.06	34.8	14.7
	1938	854	598	2.10	2.02	18.0	12.1

appears to have little or no effect on the utilization of potash, or on the fixation of potash in unavailable form, under the practical conditions of this investigation.

The Fixation of Potash in Unavailable Form

In general the amounts of potash found in the exchangeable state are much smaller than the quantities applied in soluble form as muriate of potash. Table 5 illustrates this by comparing the rate of application with the increases in available potash found in the fertilized samples from the McClary farm.

It is not intended that a quantitative significance be attached to the individual figures for "potash not accounted for" on Table 5, but the relative magnitude of these values leaves no doubt that a considerable amount of

TABLE 5.—RECOVERY OF APPLIED POTASH AS AVAILABLE POTASH IN THE MCCLARY SAMPLES
(The figures represent pounds per acre)

Treatment	K_2O applied	Recovered as available K_2O	K_2O not accounted for	Recovery of 2nd application as available K_2O
K	63	33	30	
KR	63 + 63	39	87	6
2K	126	19	107	
2KR	126 + 126	50	202	31
K3P	63	16	47	
K3PR	63 + 63	18	108	2
2K3P	126	21	105	
2K3PR	126 + 126	16	236	0
KCa	63	25	38	
KCaR	63 + 63	27	99	2
K3PCa	63	0	63	
K3PCaR	63 + 63	30	96	30

the applied potash is no longer present in exchangeable form. Part of this disappearance may be attributed to increased removal by the plants growing on potassium treated plots. However, this increased consumption is much too small to account for the loss, as is illustrated in Table 6. Leaching also is to be discounted as a factor in the disappearance of potash according to Truog and Jones (8). The data presented indicate that a large part of the applied potash has become fixed in the soil in unavailable (non-exchangeable) form.

Another point of interest which is suggested by the data of Table 5 is that a larger proportion of the first application (applied in 1935) than of the refertilization (1937) remained available at the time of sampling (1938). The reverse might be expected, as the earlier treatment has been longer in contact with the soil and the growing plants. One explanation which suggested itself was that meteorological conditions following the second application were such as to promote unavailable fixation to a much greater extent than occurred after the first application. Inspection of the meteorological records of the Lennoxville Station for the period in question failed, however, to lend any definite support to this assumption. The view of Bray and DeTurk (1) that an equilibrium tends to be set up between the exchangeable and non-exchangeable potassium may supply the basis of an alternative explanation.

Table 6.—Potash balance sheet*

Farm	Plot	K_2O added	Increase in available K_2O	Increase in K_2O consumed by plants	Balance of K_2O—presumably fixed
McClary	2KR	252	50	15	187
	2K3PR	252	16	19	217
McVittie	2KR	252	145	26	81
	2K3PR	252	72	63	117

* The figures represent pounds per acre.

The fact that potassium may be fixed in non-exchangeable form has become widely recognized in recent years. Repeated wetting and drying of the soil seems to be important in promoting this type of fixation. Volk (11) concluded that non-exchangeable fixation might be due to the synthesis of muscovite or a similar mineral. This theory is disputed by Gorbunon (3) who suggests that the ageing of soil gels which accompanies drying is responsible. He considers that the drying process destroys the outer diffusion layer, the ions of which are transferred to the inner surface of the colloidal micelles, and that the process is not completely reversible, so that on re-wetting the outer layer is only partially re-established. Vazhenin (10) and Joffe and Kolodny (5) were led to conclude that potassium fixation is associated with clay colloids having a definite lattice structure. Truog and Jones (8) offer the explanation that drying draws the layers of a crystal lattice very close together, and the potassium ion when present exerts a

powerful attraction which prevents re-expansion of the lattice on wetting. A loss of exchange capacity equivalent to the amount of potassium fixed is observed.

It was thought to be of interest to get some idea of the capacity of the soils under study to fix potash in unavailable form, and perhaps some information regarding the agencies responsible for fixation. The method of Volk (11) was applied to obtain this information.

Soil samples from the Nil and 2KR plots of each farm were selected and 30 gram portions were placed in 750 cc. Erlenmeyer flasks. To each of these was added 40 ml. of water containing KCl to equal an application of 1000 lb. of K_2O per acre, assuming 2,000,000 pounds of surface soil per acre. The samples were dried at 70° C., re-moistened with 30 ml. of water and again dried at 70° C., after which the content of available potash was determined as usual. The results of these determinations are given in Table 7.

The capacities of these soils to fix potash in unavailable form as measured in this way vary from 15.4% to 57.4%. The capacity to fix is greater in the lower layer. The data for ignition loss (McClary samples only) in the last column of Table 7 indicate that there is an appreciable difference in organic matter content between the two layers. If the fixation capacity is related to the irreversibility of the soil colloids, or is a property of crystalloids only, it might be expected to vary inversely with the organic matter content, although a direct or linear relationship is perhaps unlikely.

Table 7.—Capacity of soils to fix potash*

Sample designation	Available K_2O originally present	K_2O theoretically available after addition of KCl	K_2O available after wetting and drying twice at 70° C.	Amount of K_2O fixed	Per cent of K_2O fixed	Ignition loss %
McClary						
Nil, 0–1	300	1300	1100	200	15.4	11.32
Nil, 1–3	128	1128	706	422	37.4	8.22
2KR, 0–1	488	1488	1168	320	21.5	10.83
2KR, 1–3	210	1210	745	465	38.4	8.19
McVittie						
Nil, 0–1	308	1308	736	572	43.7	
Nil, 1–3	86	1086	462	624	57.4	
2KR, 0–1	877	1877	1121	751	40.3	
2KR, 1–3	312	1312	659	653	49.8	
Pope						
Nil, 0–1	–	–	–	–	–	
Nil, 1–3	415	1415	709	696	49.2	
2KR, 0–1	924	1924	1220	704	36.6	
2KR, 1–3	394	1394	749	645	46.3	

* Figures represent pounds of K_2O per acre.

In the laboratory test the McClary soil shows the least tendency to fix potash, whereas under field conditions it appears to be very active in this respect. The McClary field was the poorest producer of the three, the reason for which was evidently that it was the most subject to drought

because of its exposed and sloping topography. All available evidence points to repeated wetting and drying as being a most important factor in promoting unavailable fixation, which may account for the enhanced activity of the McClary soil under practical conditions. Evidently the laboratory determination may not be relied upon entirely to predict the fixation which will occur in the field.

Various materials were tested to see if they had any effect on potash fixation when added to soil. A composite specimen of untreated soil from the McVittie pasture was used for this purpose.

The materials to be tested, as detailed in Table 8, were added to 100-gm. portions of the soil, which were then moistened and dried at 75° C., and the available potash determined. The results are given in

TABLE 8.—THE INFLUENCE OF VARIOUS ADDED MATERIALS ON POTASH FIXATION*

Material added to soil	No potash applied		Potash applied at rate of 1000 lb. per acre	
	Available K_2O after drying at 75° C.	K_2O fixed due to addition	Available K_2O after drying at 75° C.	K_2O fixed due to addition
Nil	141		398	
2.5 gm. colloidal SiO_2	111	30	497	−90
2.5 gm. colloidal Al_2O_3	98	43	278	120
2.5 gm. Lloyd's Reagent	128	13	342	56
2.5 gm. $Ca(OH)_2$	135	6	163	235
0.05 gm. $CaH_4(PO_4)_2H_2O$	107	34	287	111

* The figures represent pounds per acre.

column 2, and the differences apparently due to the additions are noted in column 3, of Table 8. A similar series was prepared to which KCl was added at the rate of 1000 lb. of potash per acre; this series also was dried at 75° C., and the available potash determined. The results and observed differences are recorded in the last two columns of Table 8.

Where no potash was added the colloidal alumina seemed to be most effective in decreasing the available potash, while lime was the least effective addition. The effect of phosphate appears to be important in view of the relatively small amount added.

The results where soluble potash was added are somewhat at variance with the foregoing, as silica seems to have a negative rather than a positive influence on fixation, and lime now appears to be the most effective agent. Again phosphate has a high fixing power considering the relative smallness of the addition. However, none of the added materials have great fixing power in comparison with the soil itself, which fixes 60% of the added potash.

The results of the above experiment are considered to be of doubtful significance, and they do not shed much light on the question of what constituents of these soils are responsible for the fixation of potash in unavailable form. Reasonable confirmation is seen in the data for the suggestion previously made, that soluble phosphate in the soil promotes the unavailable fixation of potash. A final conclusion in this regard must await further experimentation.

SUMMARY

Potash fertilization improves the sward of Quebec permanent pastures by increasing the clover and useful grasses and decreasing the bare ground and moss. It increases the potash content of the herbage, and consequently the potash removal by the herbage.

In general the amount of available potash found in the surface 3-inch layer of soil is increased by top-dressing with muriate of potash. Within this layer the concentration of available potash decreases from the surface downward, being higher in the topmost 1-inch layer: this is true of both fertilized and unfertilized soil. Applied potash is firmly held and tends to remain close to the surface; however, there is a considerable penetration into the 1″–3″ layer.

Where superphosphate has accompanied the potash treatment the amount of available potash found in the soil is less than where potash was applied alone. Statistically this difference is significant. Part of the decrease is accounted for by the greater uptake of potash from the phosphate treated plots, due to increased yields. It appears likely that, in addition, soluble phosphate promotes the fixation of potash in unavailable form.

The data presented show that a considerable part of the applied potash becomes fixed in non-exchangeable form. Laboratory experiments confirmed the fact that the soils readily fixed large amounts of potash in this form. The results obtained gave confirmation that the inorganic constituents are responsible for the non-exchangeable fixation, and that soluble phosphate is effective in promoting it.

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SOIL MOISTURE STUDIES

II. SOME RELATIONSHIPS BETWEEN MOISTURE MEASUREMENTS AND MECHANICAL ANALYSIS[1]

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The first paper of this series (8) dealt with a number of factors affecting the moisture holding capacity of the soil. The present paper embodies a report of studies of the moisture holding capacity and other soil moisture measurements, and of the relationships between these measurements and the textural properties of the soil. In the third paper of the series, it is proposed to make an application of the results of these studies to soils classification.

In 1932, soil moisture studies were commenced by the senior author for specific application to irrigation tests on apple trees. These studies developed into a general investigation of the different forms of soil moisture and of certain factors affecting them. Among the practical uses that it was anticipated might be made of the resulting information was the development of a supplementary soils classification based on soil moisture properties rather than on the mechanical analysis. Before such a step could be taken, however, it became evident that it would be necessary to study the relationships between the soil moisture properties and the textural properties in some detail. It would also be necessary to determine whether the mechanical analysis, as recorded in the course of the usual soil surveys, could be used without too much error in estimating the moisture holding capacity and the other soil moisture measurements under consideration. An investigation into these phases of the problem was accordingly instituted by the authors in 1936. The work of 1936 and 1937 was so promising that a comprehensive program was outlined for 1938. As the previous findings were similar to those of 1938, it will be considered sufficient to report those of this one year only.

REVIEW OF LITERATURE

A great deal of work has been reported on the general relationships between the textural properties and the moisture properties of a soil. In very few cases, however, have these relationships been placed on a strictly mathematical basis. In so far as the moisture properties dealt with in this paper are concerned, the moisture holding capacity appears to be the only one that has been related mathematically to the soil texture by previous investigators. In 1895, Loughridge (4) studied the relationship between the moisture holding capacity of a soil and its mechanical analysis, but did not obtain a definite correlation between them. In 1927, Lebedeff (3) found a close relationship between the size of the particles in soil separates, and their ability to retain moisture against an external pull. In 1937, Olmstead (6) obtained the following formula:

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$$\text{Moisture holding capacity} = 7.7 + 0.063\%\ \text{silt} + 0.371\%\ \text{clay} + 1.79\%\ \text{organic matter}$$

The probable error was only ± 1.3. In addition he obtained the following correlations between the moisture holding capacity and other soil measurements: % clay, +0.79; % sand, −0.56; % silt, no correlation; moisture equivalent, +0.93. Various methods of determining the moisture holding capacity have already been reviewed by one of the authors (8).

PROCEDURE

The areas selected for field sampling were the orchard districts surrounding the city of Kelowna. Although a wide variability in soil texture was encountered, the soils selected all fall in the general classification of northern dark brown earths. Their pH varies as a rule from about 6.8 to 7.2 in the A horizon, and from 7.6 to 8.2 in the B horizon. In the Kelowna district, the annual precipitation averages about 13.0 inches (8-year average). Of this, about 5.2 inches fall from April to September inclusive. Thus for orchard production it is found necessary to irrigate fairly heavily. The annual mean temperature ranges around 46° F., the monthly means varying from 24.6 in January to 68.6 in July. The natural vegetation is variable, but consists for the most part of western yellow pine (*Pinus ponderosa* Dougl.), Douglas fir (*Pseudotsuga taxifolia* Britt.), and bunch grasses *(Agropyron)*.

The general procedure in the 1938 investigations involved the determination of the moisture holding capacity under field conditions, the mechanical analysis of the soil samples, and the determination of the wilting coefficient and settling volume. The specific procedure in each case was as follows.

1. *Field Capacity*

At 24 hours after the conclusion of an irrigation, or as close to 24 hours as possible, soil samples were collected for the determination of the field capacity, i.e., the moisture holding capacity under field conditions (8). Samples were taken directly under the furrows, at a depth of 8 to 12 inches. A sampling can 3 inches in diameter, 4 inches high, and of known volume was used. As far as possible, locations were selected that were not subject to seepage or other such abnormal conditions. The soil was weighed, screened through a 3 mm. sieve, and mixed thoroughly. Samples containing more than a very small percentage of gravel were discarded. The moisture content was determined by oven-drying a 100-gm. aliquot, the remainder of the sample being allowed to air-dry for use in further laboratory work. From the data thus obtained were determined the field capacity, in percentage of dry weight, and the volume weight of the soil. From these two measurements the field capacity per unit volume was calculated. It was expressed in terms of inches of water per foot of soil, and was calculated by the following formula:

$$\text{F.C.F.} = 0.12 \times \text{V.W.} \times \text{F.C.},$$

in which

F.C.F. = field capacity per foot of soil,
V.W. = volume weight,
F.C. = field capacity in percentage

A total of 100 samples was thus obtained and studied. A few of these samples were obtained from seepage or other abnormal areas, for comparison with the normal areas. The "abnormal" samples were not included in the field capacity correlations, but were used for the laboratory determinations noted below. The soils represented ranged from coarse sands to heavy clays, with the majority of them on the lighter side. None of them contained more than a very small percentage of organic matter, and there was no evidence of alkali.

2. *Wilting Coefficient*

The method used was the soil cohesion method of Bouyoucos (2). The procedure involves the gradual addition of water to oven-dried soil until it is just wet enough to stick to a spatula pressed down upon it. The moisture content at this point is termed the permanent wilting point, or the wilting coefficient. In preliminary tests by the authors on a few soil samples, the results by this method gave a good approximation to those obtained by the sunflower method.

3. *Available Moisture*

This was determined simply by deducting the wilting coefficient from the field capacity. It was expressed both in percentage and in inches of water per foot of soil. The available moisture is assumed to represent that amount of water in the soil that is available for plant use.

4. *Mechanical Analysis*

All soils were mechanically analyzed by the Bouyoucos hydrometer method (1). This method has been criticized as being essentially qualitative and of an empirical nature. It is, however, consistent, reasonably accurate, and rapid. The results, in spite of being empirical, are of value in defining soil textural characteristics. The soil particles are dispersed in water by an electrical mixer. The mixture is poured into tall glass cylinders, and the material in suspension determined at definite time intervals by means of a specially calibrated hydrometer. From these data the soil texture is calculated. The following separations were made: combined sand (1.0 to 0.5 mm.), silt (0.05 to 0.005 mm.), clay (below 0.005 mm.), and colloids. The latter term is used to designate an arbitrary separation in which colloids include clay plus the fine silt fraction.

5. *Settling Volume*

The use of the settling volume was introduced by Middleton and Byers (5) in 1934. The procedure as recommended by them was, however, modified in this investigation in several respects. Where they recommended allowing the soil to settle in a medium of distilled water, a saturated solution of ammonium sulphate was used. The results were practically the same by either method, but the use of the saturated solution produced settling very quickly. Solutions of a number of other soluble salts were found to give similar results. Some variability was encountered in the readings as a result of differences in the amount of air trapped in the mixture when shaken. Accordingly, an attempt was made to eliminate this source of error. The procedure finally adopted was as follows: pour about 60 cc.

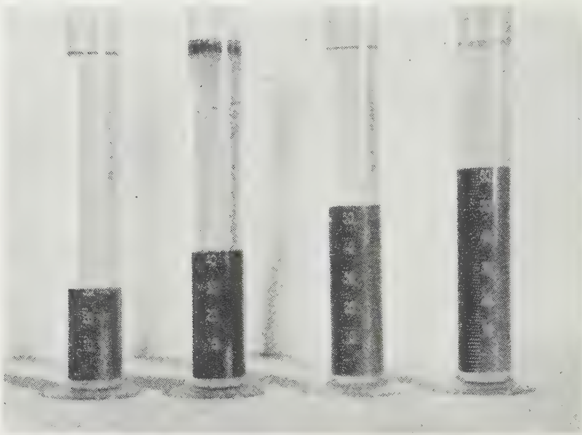

FIGURE 1. The range in settling volume was from about 30 to 65, representing soil types all the way from coarse sands to heavy clays.

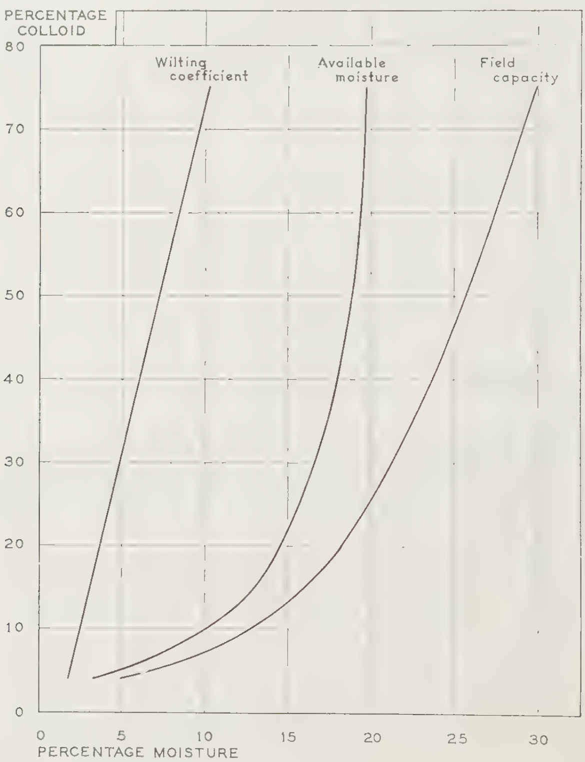

FIGURE 2. Freehand curves representing the lines of trend of the distribution obtained by plotting the percentage colloid against the wilting coefficient, available moisture content, and field capacity respectively, expressed in percentage dry weight. The wilting coefficient—percentage colloid regression line (practically the same as the corresponding curve shown above) is being used by the authors for determining the wilting coefficient in per cent from the percentage colloid.

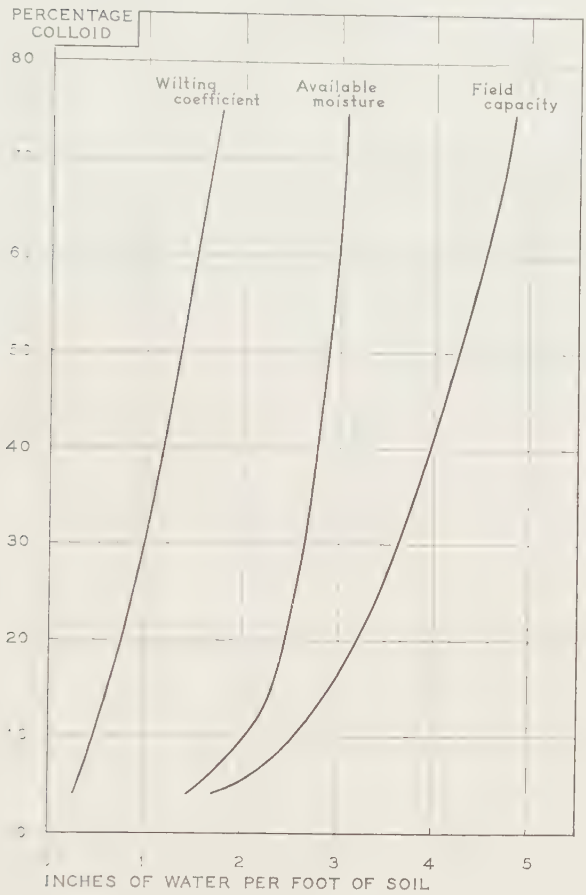

FIGURE 3. Freehand curves representing the lines of trend of the distributions obtained by plotting the percentage colloid against the wilting coefficient, available moisture content, and field capacity respectively, expressed in inches of water per foot of soil. The wilting coefficient—percentage colloid regression line (almost the same as the corresponding curve shown above) is being used by the authors for determining the wilting coefficient in inches from the percentage colloid.

of saturated ammonium sulphate solution into a 100 cc. graduate; weigh out just 50 gm. of sieved and dried soil, and pour slowly into graduate; fill to the 100 cc. mark with more solution; allow to stand for 15 minutes or more, in order to ensure complete wetting of the soil; place the palm of the hand over the mouth of the graduate, turn it pointing downwards at an angle, and shake vigorously until all the soil has been washed from the bottom; stand graduate upright at an angle, insert a long, strong stirring rod right to the bottom, and stir slowly for one minute, the purpose being to allow most of the air to escape from the mixture; wash down the soil still adhering to the inside top of the graduate; set the graduate on a level table for 24 hours, then take the reading of the soil level, in cubic centimetres; add to this one-fourth of the volume of organic matter floating on the surface. The reading thus obtained represents the settling volume

(Figure 1). Below a reading of 34 cc., the settling volume has been found to represent soil texture inaccurately. A fine gravel may give the same reading as a coarse sand.

RESULTS

Experimental Data

The data obtained in the course of the investigation are summarized in Table 1. In this table the figures shown in italics are those which, as a result of seepage, obvious experimental error, or other causes, are considered to be unreliable, and which therefore have not been used in making the various calculations discussed below. All data depending on these questionable figures have been omitted from the table.

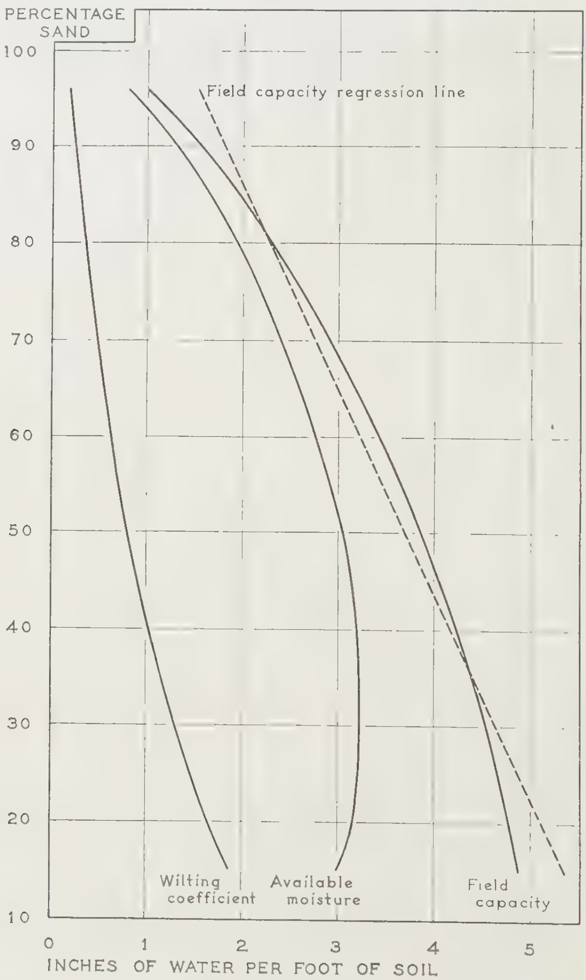

FIGURE 4. Freehand curves representing the lines of trend of the distributions obtained by plotting the percentage sand against the wilting coefficient, available moisture content, and field capacity respectively, expressed in inches of water per foot of soil. The field capacity—percentage sand regression line may be used with a fair degree of accuracy for determining the field capacity in inches from the percentage sand.

TABLE 1.—SOIL MOISTURE AND MECHANICAL ANALYSIS RECORDS*

Soil sample number	Sand	Silt	Clay	Colloid	Volume weight	Settling volume	Field capacity†		Wilting coefficient†		Available moisture†	
	%	%	%	%	.		%	in.	%	in.	%	in.
1	89.6	7.4	3.0	5.2	1.61	35.0	8.5	1.64	1.8	0.37	6.7	1.27
2	80.4	14.0	5.7	10.8	1.68	38.0	15.2	3.06	3.0	0.60	12.2	2.46
3	80.8	14.0	5.2	10.0	1.51	38.5	15.5	2.81	2.6	0.47	12.9	2.34
4	80.0	16.4	3.6	8.8	1.51	39.5	13.6	2.46	1.9	0.34	11.7	2.12
5	74.0	20.4	5.6	10.0	1.58	41.0	17.0	3.22	2.0	0.38	15.0	2.84
6	96.6	3.4	0.0	0.8	1.58	33.5	3.9	0.74	0.8	0.15	3.1	0.59
7	97.2	2.8	0.0	2.4	1.60	32.5	3.8	0.73	1.5	0.29	2.3	0.44
8	87.0	11.2	1.8	5.0	1.55	37.0	8.9	1.66	2.0	0.37	6.9	1.29
9	82.2	15.2	2.6	4.6	1.58	39.5	13.1	2.48	2.0	0.38	11.1	2.10
10	96.6	3.4	0.0	2.0	1.64	33.5	4.5	0.88	1.0	0.20	3.5	0.68
11	82.6	13.8	3.6	8.0	1.57	39.0	14.6	2.73	1.8	0.34	12.8	2.39
12	79.6	19.6	0.8	7.2	1.64	37.0	13.4	2.63	2.7	0.53	10.7	2.10
13	80.0	17.8	2.2	4.6	1.44	43.0	15.2	2.62	2.3	0.40	12.9	2.23
14	26.4	63.2	10.4	18.4	1.51	40.0	14.4	2.61	3.2	0.58	11.2	2.03
15	62.4	33.2	4.4	10.0	1.44	41.0	13.3	2.30	2.1	0.36	11.2	2.03
16	64.0	26.0	10.0	17.2	1.56	43.0	15.3	2.86	3.6	0.67	11.7	2.10
17	59.2	34.8	6.0	15.6	1.48	48.5	*22.4*	–	2.6	0.46	–	–
18	66.8	30.4	2.8	5.4	1.49	39.5	15.2	2.72	2.0	0.36	13.2	2.36
19	83.6	12.8	3.6	[illegible]	1.60	37.5	12.8	2.46	2.1	0.40	10.7	2.06
20	82.0	16.0	2.0	8.8	1.72	39.5	14.3	2.95	1.8	0.37	12.5	2.58
21	16.0	33.2	50.8	66.8	1.33	62.0	26.8	4.27	8.8	1.40	18.0	2.87
22	40.0	24.4	35.6	46.8	1.50	56.0	25.7	4.63	6.3	1.13	19.4	3.49
23	57.2	24.0	18.8	24.0	*1.83*	50.0	*13.7*	–	4.5	–	–	–
24	65.2	24.8	10.0	16.0	1.41	46.0	20.2	3.42	3.0	0.51	17.2	2.91
25	81.6	17.4	1.0	6.0	1.59	37.5	12.6	2.41	2.0	0.38	10.6	2.03
26	66.4	25.6	8.0	16.4	1.54	46.5	21.7	4.01	3.6	0.66	18.1	3.35
27	78.4	15.6	6.0	14.8	1.73	42.5	13.6	2.82	3.0	0.62	10.6	2.20
28	69.6	26.0	4.4	12.0	1.58	44.0	17.8	3.37	2.6	0.49	15.2	2.88
29	19.2	36.8	44.0	64.0	1.32	60.5	27.7	4.38	9.2	1.46	18.5	2.92
30	64.0	35.2	0.8	19.2	1.56	46.0	14.8	2.77	2.9	0.54	11.9	2.23
31	29.6	53.2	17.2	58.8	1.46	61.0	25.6	4.49	8.7	1.52	16.9	2.97
32	20.4	15.6	64.0	68.8	1.33	66.0	28.4	4.53	10.7	1.71	17.7	2.82
33	24.4	20.8	54.8	62.8	1.39	64.5	27.6	4.61	9.8	1.61	17.8	3.00
34	34.4	24.0	41.6	49.6	1.34	58.0	26.8	4.31	7.0	1.12	19.8	3.19
35	39.2	23.2	37.6	46.0	1.37	57.5	26.4	4.34	5.7	0.94	20.7	3.40
36	31.6	36.8	31.6	51.6	1.44	59.0	25.0	4.32	5.8	1.00	19.2	3.32
37	25.6	19.6	54.3	61.2	1.43	62.0	27.6	4.74	8.8	1.51	18.8	3.23
38	34.0	22.4	43.6	48.8	1.44	60.5	27.1	4.68	7.2	1.25	19.9	3.43
39	18.8	18.4	62.8	72.0	1.34	64.0	30.9	4.96	10.0	1.61	20.9	3.35
40	22.4	22.8	54.8	62.8	1.30	62.0	26.8	4.18	9.1	1.42	17.7	2.76
41	15.6	20.8	63.6	75.6	1.12	63.0	31.5	4.23	10.9	1.46	20.6	2.77
42	22.8	22.2	50.0	58.0	1.36	61.5	23.9	3.90	7.7	1.26	16.2	2.64
43	64.8	32.6	2.6	6.8	1.57	40.0	*21.6*	–	1.8	0.34	–	–
44	64.8	26.8	8.4	15.6	1.59	41.0	13.8	2.63	3.1	0.59	10.7	2.04
45	43.6	20.0	36.4	46.0	1.51	57.0	20.9	3.78	6.8	1.20	14.1	2.58
46	56.0	19.6	24.4	29.6	1.58	49.5	20.6	3.91	5.3	1.01	15.3	2.90
47	46.8	22.8	30.4	35.6	1.45	53.0	21.5	3.74	5.0	0.87	16.5	2.87
48	75.4	17.4	7.4	12.8	1.72	37.5	13.4	2.76	3.1	0.64	10.3	2.12
49	49.6	17.6	32.8	38.8	*1.75*	50.0	20.1	–	5.5	–	14.6	–
50	72.4	21.2	6.4	12.0	1.68	37.5	15.5	3.12	3.3	0.66	12.2	2.46
51	78.0	18.4	3.6	7.6	1.60	36.0	14.3	2.74	2.4	0.46	11.9	2.28
52	82.4	14.4	3.2	6.8	1.63	37.0	11.2	2.19	2.8	0.55	8.4	1.64
53	20.4	15.6	64.0	68.8	1.34	61.0	28.1	4.52	10.3	1.66	17.8	2.86
54	24.4	15.2	60.4	64.8	1.35	60.5	26.3	4.26	10.0	1.62	16.3	2.64
55	18.4	19.2	62.4	72.8	1.34	61.0	28.2	5.43	8.1	1.30	20.1	3.23
56	30.4	25.6	44.0	52.4	1.60	48.0	25.4	4.88	6.3	1.21	19.1	3.67
57	13.6	57.2	29.2	75.6	1.37	66.0	31.2	5.13	10.1	1.66	21.1	3.47
58	17.2	18.8	64.0	71.6	1.22	64.0	28.2	4.12	9.7	1.42	18.5	2.70
59	79.4	11.0	9.6	12.8	1.58	41.0	*10.4*	–	3.6	0.68	–	-
60	36.8	38.0	25.2	30.8	1.51	54.0	20.9	3.78	5.4	0.98	15.5	2.80
61	32.4	19.2	48.4	56.8	1.45	59.0	27.1	4.72	8.0	1.40	19.1	3.32

Table 1.—Soil moisture and mechanical analysis records*—*Concluded*

Soil sample number	Sand	Silt	Clay	Colloid	Volume weight	Settling volume	Field capacity†		Wilting coefficient†		Available moisture†	
	%	%	%	%			%	in.	%	in.	%	in.
62	78.0	11.2	10.8	13.2	1.58	45.0	*18.3*	–	3.1	0.59	–	–
63	70.0	20.8	9.2	15.6	1.49	46.0	*22.5*	–	3.6	0.64	–	–
64	82.4	10.4	7.2	9.2	1.72	37.0	12.5	2.58	2.6	0.54	9.9	2.04
65	83.2	11.6	5.2	8.4	1.55	34.5	9.4	1.74	2.4	0.45	7.0	1.29
66	96.4	3.0	0.6	1.4	1.61	32.0	4.9	0.95	0.8	0.15	4.1	0.80
67	70.4	12.8	16.8	20.8	*1.73*	46.0	16.7	–	3.6	–	13.1	–
68	64.8	12.4	22.8	22.8	*1.76*	50.0	13.1	–	5.0	–	8.1	–
69	40.8	10.4	48.8	48.8	1.42	60.0	25.1	4.28	7.1	1.21	18.0	3.07
70	84.4	12.0	3.6	6.0	1.62	34.0	9.1	1.77	1.8	0.35	7.3	1.42
71	88.8	10.8	0.4	5.2	1.67	31.5	7.1	1.42	1.9	0.38	5.2	1.04
72	87.2	10.8	2.0	4.6	1.58	35.5	10.7	2.02	1.8	0.34	8.9	1.68
73	92.8	6.2	1.0	2.6	1.65	32.0	7.3	1.44	1.4	0.28	5.9	1.16
74	95.2	4.2	0.6	2.4	1.61	33.5	5.3	1.02	1.2	0.23	4.1	0.79
75	97.0	3.0	0.0	1.2	1.60	34.5	4.8	0.92	1.3	0.25	3.5	0.67
76	98.0	2.0	0.0	0.6	1.60	33.0	5.5	1.05	1.6	0.31	3.9	0.74
77	74.8	21.6	3.6	10.0	1.60	36.5	14.4	2.76	2.3	0.44	12.1	2.32
78	55.2	38.0	6.8	16.0	*1.65*	46.0	19.9	–	3.8	–	16.1	–
79	56.4	38.8	4.8	12.4	*1.43*	44.0	19.2	–	3.0	–	16.2	–
80	42.8	42.4	14.8	27.2	1.45	44.0	15.9	2.76	4.5	0.78	11.4	1.98
81	53.6	34.0	12.4	19.6	1.48	46.5	17.0	3.02	3.7	0.66	13.3	2.36
82	53.2	32.0	14.8	22.0	1.48	46.5	16.8	2.98	3.9	0.69	12.9	2.29
83	53.6	29.2	17.2	23.6	1.52	47.0	16.1	2.94	3.4	0.62	12.7	2.32
84	58.0	31.2	10.8	17.6	1.51	43.5	18.9	3.42	2.8	0.51	16.1	2.91
85	68.0	20.8	11.2	16.8	1.59	41.0	15.6	2.97	4.0	0.76	11.6	2.21
86	76.0	18.8	5.2	11.2	1.52	40.5	16.0	2.92	2.7	0.49	13.3	2.43
87	59.6	32.0	8.4	16.4	1.40	48.0	*25.8*	–	3.2	0.54	–	–
88	46.4	38.8	14.8	22.4	1.35	49.0	*28.0*	–	4.2	0.68	–	–
89	36.8	42.8	20.4	32.4	1.38	51.0	*27.1*	–	*1.3*	–	–	–
90	37.2	38.0	24.8	34.8	1.31	52.5	*28.8*	–	*2.7*	–	–	–
91	32.8	51.2	16.0	26.4	1.39	49.0	*27.4*	–	*2.6*	–	–	–
92	61.2	29.2	9.6	14.8	1.62	43.5	17.1	3.33	3.4	0.66	13.7	2.67
93	62.8	29.2	8.0	12.4	1.60	43.5	16.9	3.24	2.6	0.50	14.3	2.74
94	70.0	26.4	3.6	10.0	1.63	41.0	14.6	2.86	2.4	0.47	12.2	2.39
95	75.6	18.8	5.6	10.4	1.70	37.5	10.6	2.16	2.5	0.51	8.1	1.65
96	78.4	15.2	6.4	11.6	1.61	38.5	13.6	2.63	3.1	0.60	10.5	2.03
97	80.8	15.6	3.6	9.2	1.62	38.0	11.6	2.26	2.6	0.51	9.0	1.75
98	73.2	21.2	5.6	12.8	1.70	40.5	14.7	3.00	3.5	0.72	11.2	2.28
99	79.6	14.4	6.0	10.4	1.68	38.5	15.2	3.07	2.1	0.42	13.1	2.65
100	84.0	12.4	3.6	8.0	1.63	37.5	14.5	2.84	2.5	0.49	12.0	2.35

* The figures in italics are considered unreliable, due to seepage or other sources of error, and are not used in calculating correlations and regressions. All data that are directly dependent on these unreliable figures have been omitted from the table.

† Each of the three moisture contents is expressed in two ways: *(a)* in percentage dry weight of soil, *(b)* in inches of water per foot of soil.

Scatter Diagram Studies

As a basis for statistical analysis of the data obtained, scatter diagram studies were made of practically all pairs of records. In almost every case, very close relationships were found to exist. Through the plotted distributions, free-hand curves were drawn representing the lines of trend. A number of these curves are illustrated in Figures 2 to 5. In Figure 2, it will be seen that the percentage colloid wilting coefficient (in per cent) curve is a straight line, but that the percentage colloid—field capacity (in per cent) curve is a definite curve. As the colloid content increases, there is at first a very rapid increase in the field capacity, followed in the

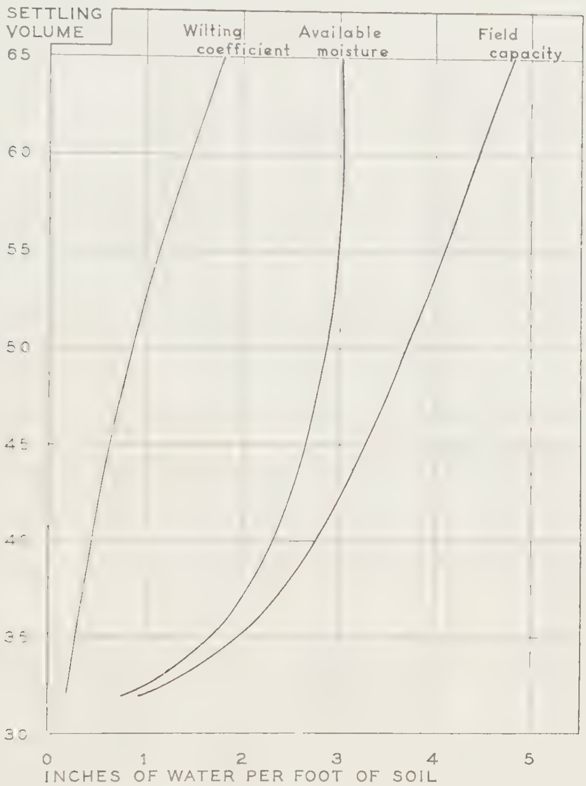

FIGURE 5. Freehand curves representing the lines of trend of the distributions obtained by plotting the settling volume against the wilting coefficient, available moisture content, and field capacity respectively, expressed in inches of water per foot of soil.

heavier soils by a much slower increase. This lessening in the increase of the field capacity is sufficient to cause the difference between this measurement and the wilting coefficient (i.e., the available moisture) to increase to about 20% only. Above 60% colloid, the available moisture shows no further increase. A similar situation is encountered when the moisture content is expressed in inches instead of per cent (Figure 3); that is, the available moisture shows no further increase above about 60% colloid. It might be noted that multiplying by the volume weight has changed the shape of the curves somewhat: the wilting coefficient, for instance, no longer gives a straight line trend with percentage colloid. Charting against percentage sand and settling volume (Figures 4 and 5) reveals a similar type of available moisture curve in each case. This is due to the fact that as the soil gets heavier, the field capacity increases at a decreasing rate, whereas the wilting coefficient increases at an increasing rate; thus there comes a time when the wilting coefficient is increasing just as rapidly as the field capacity, so that the difference between them tends to remain constant, or even to decrease. There is very little if any increase in the available moisture above 40% sand or above a settling volume of 55. The curves illustrated in these figures are quite typical of the general trends.

Correlations

The coefficients of correlation that are of especial interest are presented in Table 2. In calculating the field capacity and available moisture correlations, the data obtained from the samples from seepage or other distinctly abnormal areas were omitted. In every case except one, the coefficients had "P" values less than 0.01, and could therefore be considered "highly significant". The exception was the volume weight—% silt correlation, which had a "P" value between 0.01 and 0.05, and was accordingly classified as "significant". It will be noted from Table 2 that especially high correlations were obtained between the following pairs: *(a)* field capacity and % sand, *(b)* wilting coefficient and % colloid, and *(c)* settling volume and % sand. It might be noted that by the method of computation used, the % sand was exactly complementary to the % silt + clay. It appears obvious that the high negative correlations obtained between the various soil moisture measurements and the % sand really signify equally high positive correlations between these measurements and the % silt + clay. The exceptionally high correlation between the % sand and the settling volume indicates that the settling volume reading is very closely dependent upon the percentages of silt and clay in the sample. The high correlations between the settling volume on the one hand and the % sand, the % clay, and the % colloid on the other hand suggest that the settling volume should prove a satisfactory measurement for expressing soil texture in one composite figure. It will also be noted that the settling volume gave close correlations in nearly every case with the moisture measurements. The coefficients of the moisture measurements with volume weight were lower than might have been anticipated. This was due in part to the fact that the volume weights were determined under field conditions, and were therefore subject to such variable factors as differences in horizon represented, salts of deposition, compaction by implements, etc., (8). Wherever a high correlation was obtained in these studies, it was found to be the result of a straight or nearly straight line of trend, about which the points of the distribution clustered rather closely.

TABLE 2.—COEFFICIENTS OF CORRELATION

	Percentage sand	Percentage silt	Percentage clay	Percentage colloid	Settling volume
Field capacity, in %	−.930	.665	.800	.886	.891
Wilting coefficient, in %	−.914	.378	.966	.974	.947
Available moisture, in %	−.855	.657	.630	.725	.844
Field capacity, in inches	−.884	.754	.715	.821	.894
Wilting coefficient, in inches	−.941	.410	.945	.960	.950
Available moisture, in inches	−.727	.769	.510	.616	.650
Volume weight	.798	−.205	−.785	−.840	−.831
Settling volume	−.990	.350	.930	.965	—

Indirect Determination of Moisture Contents

It is one thing to have a high correlation between two sets of values, but quite another thing to determine one set from the other with any degree of accuracy. The amount of error involved in making this transference is of the greatest importance. In this particular case, straight-line

equations have been calculated for all 6 types of moisture content, and the standard errors of the estimates determined. Owing to the fact that satisfactory straight-line trends were obtained in the percentage sand-field capacity distributions and in the percentage colloid-wilting coefficient distributions, and to the fact that the available moisture can readily be determined by deducting the wilting coefficient from the field capacity, it appeared unnecessary to attempt to calculate curve equations to fit the curved lines of trend.

The straight-line equations have been calculated not only for all the single factors affecting moisture values, but also for combinations of these factors. For example, the field capacity in per cent has been determined from the percentage sand, the percentage silt, and the percentage clay, each by means of a separate equation, and in addition from the following combinations: percentage sand and percentage clay, percentage sand and percentage colloid, and percentage sand, percentage silt, and percentage clay. The same has also been done for each of the other 5 moisture values. The methods used in determining the equations and in calculating the standard errors of estimate are outlined in Chapters 6 and 13 of Snedecor's textbook on statistical method (7). The standard errors of estimate are shown in Table 3.

TABLE 3.—STANDARD ERRORS OF ESTIMATE IN THE INDIRECT DETERMINATION OF SOIL MOISTURE CONTENTS BY THE USE OF STRAIGHT-LINE EQUATIONS

Factors used in determination	Moisture content determined					
	F.C.*	W.C.	A.M.	F.C.F.†	W.C.F.	A.M.F.
Sand, %	2.19	0.98	2.30	0.476	0.137	0.486
Silt, %	4.90	2.44	3.28	0.652	0.355	0.469
Clay, %	3.54	0.87	3.21	0.682	0.100	0.820
Colloid, %	3.55	0.45	2.94	0.600	0.087	0.577
Sand %, clay %	2.65	0.71	2.52	0.451	0.099	0.435
Sand %, colloid %	2.23	0.62	2.52	0.520	0.087	0.431
Sand %, silt %, clay %	2.73	1.17	2.49	0.483	0.384	0.504
Settling volume	1.92	0.81	2.02	0.376	0.125	0.385

* F.C., W.C., and A.M. = field capacity, wilting coefficient, and available moisture, expressed in per cent.
† F.C.F., W.C.F., and A.M.F. = field capacity, wilting coefficient, and available moisture per foot of soil, expressed in inches.

The data presented in Table 3 indicate that under the conditions of this investigation, the moisture measurements can be determined from the mechanical analysis with a degree of accuracy sufficient for practical use. The field capacity can be calculated from the percentage sand, and the wilting coefficient from the percentage colloid, with only a relatively small amount of error in each case. The most logical way of determining the available moisture appears to be to calculate the field capacity and the wilting coefficient separately, then to subtract the one from the other to obtain the required figure. It will be seen from Table 3 that in two cases (field capacity and available moisture, expressed in inches), the error was somewhat lower when the figures were calculated from two soil separates rather than from just one; however, the differences were not great enough to justify the use of more than one soil separate in determining

any one moisture measurement. As is indicated by the data of Table 3, the settling volume also showed good promise for use in the indirect determination of soil moisture measurements.

As a matter of interest, the equations that have given the greatest promise for use in the Okanagan Valley are presented below. It is not suggested that any of these equations should prove satisfactory for use with soils formed under climatic conditions differing widely from those of the Okanagan Valley. In each set of three equations, the first represents the most accurate of those based on the mechanical analysis, the second the next accurate, and the third one that based on settling volume.

Field capacity in per cent
= (1) -0.276% sand $+34.28$
(2) -0.301% sand -0.0452% clay $+36.435$
(3) 0.605 settling volume -10.09

Wilting coefficient in per cent
= (1) 0.120% colloid $+1.338$
(2) -0.0515% sand $+0.060\%$ colloid $+6.106$
(3) 0.264 settling volume -8.008

Available moisture in per cent
= (1) -0.171% sand $+23.464$
(2) -0.297% sand -0.165% clay $+33.198$
(3) 0.325 settling volume -1.367

Field capacity in inches per foot of soil
= (1) -0.0546% sand -0.0205% clay $+6.768$
(2) -0.0415% sand $+5.605$
(3) 0.0760 settling volume -0.321

Wilting coefficient in inches per foot of soil
= (1) 0.020% colloid $+0.265$
(2) -0.0024% sand $+0.0170\%$ colloid $+0.485$
(3) 0.0392 settling volume -1.037

Available moisture in inches per foot of soil
= (1) -0.0824% sand -0.0672% colloid $+9.063$
(2) -0.0445% sand -0.0291% clay $+5.578$
(3) -0.0410 settling volume $+0.538$

DISCUSSION

The results presented above may be considered of value from at least two specific viewpoints. In the first place, they add to the existing knowledge of the relationships between soil texture and soil moisture properties; and in the second place, they indicate the possibility of utilizing the mass of textural data that are obtained in the course of a soil survey, to determine the moisture properties of the soil types studied. Such moisture measurements as may be determined in this way could be used either for the designation of soil moisture properties as such, or for the development of a supplementary, simplified soils classification. A suggestion for accomplishing this latter will be presented in the third paper of this series.

As noted under "Scatter Diagram Studies" above, it was found in this investigation that the heavier the soil up to about 60% colloid, the higher was the available moisture content; but that above 60% colloid the available moisture content showed no further increase. This finding has a very important application to the evaluation of soil type, both in irrigated and in non-irrigated districts. It has been a common assumption that the heavier a soil, the greater its water reservoir, and hence the longer it will support plant growth without the need for further precipitation or irrigation. On the basis of the results of this investigation, however, it can no longer be assumed that this is so. It would appear that a moderately heavy soil may contain just as large a reservoir of available moisture as does a very heavy soil. Whether this same condition accompanies an increase in the organic matter content above a certain point has not been investigated by the authors.

SUMMARY

The moisture holding capacities of 100 soil samples were determined under field conditions, about 24 hours after an irrigation, at 8 to 12 inches below the furrow. The soils varied in texture from coarse sands to heavy clays. Laboratory determinations were made of the wilting coefficient, mechanical analysis, and settling volume. The available moisture content was determined by deducting the wilting coefficient from the field capacity. By means of charts, correlations, regressions, and equations, the moisture values were compared with the mechanical analyses and settling volumes.

It was found from the charts that as the colloid content of the soil increased, the wilting coefficient at first increased less rapidly than the field capacity, with a resulting increase in the available moisture; but above 60% colloid, they increased at about the same rate, resulting in a levelling off of the available moisture content. The importance of this in practical agriculture is pointed out.

Variations in the moisture values were found to be closely associated with variations in both the mechanical analysis and the settling volume. In mathematical terms, these relationships were found to be "highly significant". There were especially high correlations between the field capacity and percentage sand, and between the wilting coefficient and percentage colloid.

Both mechanical analysis and settling volume were found to be satisfactory for use in determining the field capacity and wilting coefficient. The former could be determined with a comparatively small error of estimate by the use of equations involving percentage sand; the latter from equations involving percentage colloid.

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SOIL MOISTURE STUDIES

III. AN APPLICATION OF SOIL MOISTURE MEASUREMENTS TO SOILS CLASSIFICATION[1]

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In the first paper of this series (3), studies of the moisture holding capacity and of certain factors affecting it were outlined. In the second paper, the mathematical relationships between the moisture properties and the textural properties of 100 soil samples collected in the Okanagan Valley were presented. It is now proposed to suggest a means of utilizing the soil moisture properties for the development of a simplified soils classification supplementary to that of the usual soil survey.

Soil moisture measurements have been used by a large number of investigators for the purpose of designating specific properties in different soil types. For the most part, however, there appears to have been little attempt to make actual application to systematic soil classification. In 1928, Hardy (1) suggested the use of the index of texture as a basis for the physical classification of soils. The index of texture was determined by deducting one-fifth of the percentage of sand from the sticky-point reading. In view of the nature of the suggestions presented below, the following comments, published by Scofield (2) after the completion of the work on which this paper is based, are of special interest: "In view of the importance of reservoir capacity as a factor determining the suitability of soils for irrigation, it is manifestly desirable that an acceptable method be devised for determining quantitatively this characteristic of the soil profile. It should be possible to ascertain either by field or laboratory tests the reservoir capacity of representative layers of the soil profile, expressed as inches of water per unit of depth. This information together with the ascertainable facts as to any physical limitations of the depth of the root zone would serve as a most useful aid in classifying and mapping soils."

PURPOSE OF SUPPLEMENTARY CLASSIFICATION

The classification of the soils in any specified area is based on the data obtained in the course of a soil survey. These data include, in part, the textural properties of the soil in each horizon of a number of selected profiles, expressed in such terms as the percentages of sand, silt, clay, and colloid present. The final division of the soil into distinct types or series depends upon such factors as soil texture, source of soil, and climate. To a large extent, a soil survey is a fact inventory. The reports of the surveys are technical in nature, and are intended for use by technical workers rather than by farmers. It is true that the results of a survey may be applied directly to many problems. For the most part, however, their

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application to practical agriculture requires supplementary investigational work. The survey is of value not only in providing the basic data for such studies, but also in indicating their need and their direction of application.

In view of the technical nature of a soil survey, the data obtained are naturally somewhat difficult for the non-technical man to understand or to place in their proper perspective. For farmer use, the original data may need to be translated into different terms. Such would appear to be the case with the textural data. The presentation of textural characteristics by the use of figures representing the percentages of gravel, sand, silt, clay, and colloid in every horizon in every profile, sometimes appears a bit confusing to the practical farmer. If the great mass of data could be simplified in some manner, it should prove easier for him to grasp and to apply.

During the past few years, the British Columbia Soil Survey Branch has, under the supervision of Mr. C. C. Kelley, conducted a survey of the arable land of the Okanagan Valley. The general procedure has been as follows: (1) the delineation of soil class boundaries, (2) the study of selected profiles, (3) the mechanical analysis of samples obtained from each horizon in each profile, and (4) the presentation of the data both in tabular form and as coloured maps. As a result of this work, there has accumulated a considerable store of valuable information, which should serve as a basis for further soil studies for some years to come.

As far back as 1932, a number of the workers in the Okanagan Valley envisioned the possibility of supplementing the initial soil survey data with a classification of soils based on their moisture properties. Several uses were pictured for such a classification. In the first place, it could be used by extension workers as a help in presenting the results of a survey to farmers, or as a help in making recommendations that are based on soil textural differences. In the second place, it could be used to obtain a better understanding of the variability in the soil moisture properties themselves. Thus, the data might assist in planning an irrigation system, in making recommendations for the efficient application of irrigation water, in determining the suitabilities of different types of plants in a district newly opened up for agricultural use, or in explaining the effects of precipitation or irrigation in areas already planted out.

SELECTION OF MOISTURE MEASUREMENT

Before any specific procedure can be suggested for the use of soil moisture measurements in the classification of soils, it becomes necessary to decide which measurement should be used as a basis. Among those measurements that have received consideration, three show special promise. These are the field capacity, the available moisture, and the amount of water necessary to apply at each irrigation.

In an irrigated district, a soil moisture measurement based on the amount of water required at each irrigation should prove of special value to both farmers and irrigation officials. Preliminary work has indicated, however, that a great deal of investigational work needs to be conducted before the measurement can be used with any degree of accuracy. One of the chief difficulties lies in the fact that when one portion of the soil

has been dried to the wilting point, other portions are still wet; and not only that, they vary a great deal in their relative wetness. Thus in an apple orchard, the soil will dry out much more quickly in the top 2 feet than at lower levels, and more quickly within a radius of 10 feet from the trunk of a tree than out in the centre of the panel. The amount of water to be applied at any one irrigation depends not only on the soil texture, but on the amount of soil permeated by the roots, on the concentration of the fibrous roots in each area, and on the rates of transpiration and evaporation. Thus there is variation in accordance with soil texture, soil depth, plant type, plant age and size, locality, season of year, amount of precipitation, etc. Sufficient data are not yet at hand to attempt a soil classification on this basis.

The moisture measurement that has appeared the most logical for use as a supplement to mechanical analysis has been the available moisture, determined by deducting the wilting coefficient from the field capacity. In so far as plant growth is concerned, this is considered to be the most important soil moisture attribute. In so far as the characterization of soil texture as such is concerned, however, it does not appear to offer as much promise. The primary difficulty lies in the fact that as the clay or colloid content of the soil increases, the available moisture content increases up to a certain point only, then tends either to remain stationary or to decrease. Thus, a soil with 55% colloid might be in the same class as one with 65 or 75% colloid. This characteristic of the available moisture content was pointed out and illustrated in the second paper of this series (4).

At the present time, the most promising soil moisture value, in so far as both moisture studies and soil classification are concerned, appears to be the field capacity, i.e., the moisture holding capacity determined in such a manner as to approximate field conditions. On the one hand, the field capacity has a definite yet simple meaning, that can readily be interpreted. On the other hand, it varies fairly uniformly with variation in soil texture (4). Furthermore, once a soil series is classified on this basis, it should be quite a simple matter to transfer the data to available moisture contents; or even to irrigation requirements, when a satisfactory method of doing this has been developed.

USE OF FIELD CAPACITY

The field capacity for water is now being used by the authors as a basis for a supplementary soil classification, both by way of supplementing the usual soil survey data and by way of making direct comparisons of the moisture holding capacities in field plot soils. The procedure used is as follows:—

(a) Map the soils on the basis of profile differences.

(b) Determine the soil texture by mechanical analysis of each horizon, in each of the profiles segregated on the map. In apple plot work in areas where the soil profiles are already thoroughly understood, the horizons are in some cases being ignored. Composite samples are taken with an auger at depths of 0 to 8 inches, 8 to 24 inches, and 24 to 60 inches. These depths represent roughly the area of cultivation, the area of greatest root concentration, and the area of lesser root concentration, respectively. The few roots descending below 5 feet are thus ignored. It is of course

recognized that no matter how the sampling is done, the mapping of the profile by horizons provides information of distinct value. Whichever method is used, separate treatment is accorded the gravelly layers encountered. In certain cases, the subsoil consists of a mixture of gravel and coarse sand, quite unsuited to normal root growth; and where this is encountered above 5 feet, samples are taken down to the gravel only. However, if good soil is mixed in with the gravel, holes are dug through it, and samples are obtained from the sides of the holes. These samples are then screened through a 3 mm. sieve, and the percentages of gravel determined. The composite samples thus obtained are analyzed mechanically or are used for settling volume determinations. As noted by Wilcox (3), the compositing of the soil from two or more horizons has been found to give similar results to those obtained from the sum of the individual horizons.

(c) The data thus obtained are transferred into field capacity per foot of soil, expressed in inches, and from that into the total amount of water held in the profile, or in those specific areas in the profile noted above. The equations used in accomplishing this have been presented in the second paper of this series (4). In making use of a single-factor equation, the procedure may of course be simplified somewhat by preparing a regression line chart and reading the answer off this chart. Examples of the methods of calculation are given in Tables 1, 2, and 3. In Table 1, representing a comparatively heavy soil type, the field capacity is calculated by horizons from the percentage sand and percentage clay. It will be noted that each figure thus obtained is first corrected for the percentage of gravel in the original sample, before multiplying by the horizon depth. It is assumed that the field capacity of particles over 3 mm. in diameter is zero. The total field capacity to 5 feet is determined simply by adding up the individual capacities of all the horizons to that depth. In this case it is 23.71 inches of water. In Table 2, representing a lighter and somewhat shallower soil, the field capacity is calculated for specified depths from the settling volume. The total field capacity thus calculated is 8.97 inches of water. In this case, sampling was discontinued at a depth of 44 inches. If so desired, the horizon data can readily be transferred into field capacities for any specified depths. This transference is illustrated in Table 3, where the data of Table 1 are transferred into field capacities for specified depths.

It is not the purpose of this paper to make actual application of the use of the field capacity, either to soil survey data or to field plot comparisons. However, an example of the use that is being made of it in the Okanagan Valley may prove of some interest. In apple nutrition studies, a total of 85 plots of McIntosh trees has been selected in widely varying soil types in 8 different districts. In addition to a profile map to a depth of 5 feet in each plot, the soil is being classified as demonstrated in Table 3. By way of illustration of the values being obtained, the results obtained in 1939 from some of the plots in East Kelowna are shown in Table 4. It will be noted that a wide range of values may be obtained in any one district, as a result of a wide range in soil texture and depth. In this particular district, the soil is in many cases less than 5 feet deep, being underlain by a mixture of gravel, stones, and coarse sand (called "gravel"

TABLE 1.—CALCULATION BY HORIZONS OF THE TOTAL MOISTURE HOLDING CAPACITY OF A SOIL PROFILE*

Horizon	Depth in inches	Gravel	Sieved soil data			F.C.F. corrected for gravel	F.C.F. × depth
			Sand	Clay	F.C.F.†		
		%	%	%			
A1	10	0	26.0	33.2	4.67	4.67	3.89
A2	18	0	11.3	48.9	5.15	5.15	7.72
B	12	5.0	5.6	63.8	5.10	4.85	4.85
C	20	10.5	15.1	52.5	4.86	4.35	7.25
Total	60						23.71

*Equation from Wilcox and Spilsbury (4). F.C.F. = −0.0546% sand −0.0205% clay + 6.768.
†F.C.F. = field capacity per foot of soil, expressed in inches.

TABLE 2.—CALCULATION BY SPECIFIED DEPTHS OF THE TOTAL MOISTURE HOLDING CAPACITY OF A SOIL PROFILE*

Depth in inches	Gravel	Sieved soil data		F.C.F. corrected for gravel	F.C.F. × depth
		Settling volume	F.C.F.†		
	%				
0– 8	0	43.6	3.00	3.00	2.00
8–24	3.8	38.4	2.60	2.50	3.33
24–44	9.0	35.5	2.38	2.19	3.64
44–60	(100% gravel and coarse sand)				0.00
Total					8.97

*Equation from Wilcox and Spilsbury (4). F.C.F. = 0.0760 S.V. −0.321.
†F.C.F. = field capacity per foot of soil, expressed in inches.

TABLE 3.—TRANSFERENCE OF FIELD CAPACITY BY HORIZONS TO FIELD CAPACITY BY SPECIFIED DEPTHS*

Specified depths in inches	Horizon	Depth in inches	F.C.F.† by horizons	F.C.F. × depth	Specified depth totals
0– 8	A1	8	4.67	3.12	3.12
8–24	A1	2	4.67	0.78	
	A2	14	5.15	6.00	6.78
24–60	A2	4	5.15	1.72	
	B	12	4.85	4.85	
	C	20	4.35	7.24	13.81
Total		60			23.71

*Using the data from Table 1.
†F.C.F. = field capacity per foot of soil, expressed in inches.

in the table) to well below the greatest root depth. It is proposed to correlate each of the 4 field capacity values (0 to 8 inches, 8 to 24 inches, 24 to 60 inches, and 0 to 60 inches) on the one hand with root distribution, tree growth, tree yields, and fruit quality on the other hand.

TABLE 4.—FIELD CAPACITIES OF SOILS IN SELECTED McINTOSH PLOTS IN EAST KELOWNA*

Plot No.	Depth to gravel	F.C.F.† × depth for three specified depths and for total profile			
		0–8 in. depth	8–24 in. depth	24–60 in. depth	Total profile
	in. of soil	in. of water	in. of water	in. of water	in. of water
K 1	14	1.80	1.22	0.00	3.02
K 7	41	1.91	3.49	4.12	9.52
K 8	54	2.59	4.78	8.89	16.26
K 9	33	2.28	3.60	1.72	7.60
K10	19	1.75	1.28	0.00	3.03
K14	22	1.28	1.44	0.00	2.72
K16	60+	3.91	3.71	10.07	17.69
K17	60+	1.92	4.79	12.20	18.91
K18	60+	2.64	5.59	12.90	21.13
K21	12	1.80	0.86	0.00	2.66
K22	19	1.54	0.90	0.00	2.44
K25	52	2.71	5.74	10.78	19.23
K49	56	2.72	5.83	12.59	21.14
K51	19	1.63	1.89	0.00	3.52
K54	21	1.91	0.88	0.00	2.79

*Expressed in inches of water. Data supplied by A. T. Knight.
†F.C.F. = field capacity per foot of soil, expressed in inches.

SUMMARY

It is suggested by the authors that the usual soil survey data could to advantage be supplemented by a classification based on soil moisture values. For this purpose, the use of the field capacity is recommended, expressed in inches of water per horizon, per unit of soil depth, or per total profile. The use of the mechanical analysis and settling volume for this purpose is illustrated, together with some results from certain field plot soils.

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WIND EROSION OF SOILS IN RELATION TO SIZE AND NATURE OF THE EXPOSED AREA[1]

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In a previous paper (4), data were presented showing that under an equal force of wind, whether in a wind tunnel or in the open field, the velocity near the surface of the ground depends entirely on the type of surface. This is due to the dominant effect of the frictional eddies on the velocity of wind. It was found that the velocity gradient conforms closely to the generally accepted Prandtl's rate of flow formula, which shows the relation between the velocity of the wind, the frictional resistance of the surface measured in dynes per unit area, and the size of the surface irregularities. This is expressed by $Vz = 5.75 \sqrt{\frac{\gamma}{\rho}} \log \frac{z}{k}$, in which Vz is the velocity at any height z, γ is the surface drag, ρ the density of the air, and k is 1/30 of the height of the surface irregularities.

Over an eroding sand surface, on the other hand, the velocity gradient of wind was found by Bagnold (1, 2, 3) to undergo a considerable change to which the original Prandtl's formula does not apply. He showed that sand movement reduces the surface velocity of wind, the reduction being caused by particles in saltation[4] decreasing the momentum of the wind. Bagnold found that over drifting sand Prandtl's formula becomes $Vz = 5.75 \sqrt{\frac{\gamma}{\rho}} \log \frac{z}{k^1} + Vt$, in which k^1 is the height of the surface ripples and Vt is the velocity at height k^1, both remaining constant for all velocities above the threshold velocity.

In order to gain further knowledge of soil drifting and its control, an investigation of the dynamic factors influencing soil movement and a study of the relation of these factors to methods of soil drifting control were undertaken. The object of the study reported in this paper was, first, to find whether or not Bagnold's rate of flow formula for drifting desert sand applies to drifting soils, and second, to find what relation exists between the intensity of soil drifting and the area and type of the exposed surface.

EXPERIMENTAL PROCEDURE

The laboratory and the portable field tunnel used have been described previously (4). Since then the exposure chamber of the laboratory tunnel has been extended to 15 feet and that of the portable tunnel to 44 feet. Figure 1 shows two views of the portable tunnel now in use.

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[1] Contribution from the Experimental Farms Service (P.F.R.A.), Dominion Department of Agriculture, Ottawa. Read to the Soils Group of the Canadian Society of Technical Agriculturists at the Twentieth Annual Meeting at Winnipeg, Man., June 19 to 22, 1940.

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[4] The movement of particles characterized by a series of jumps is termed by Bagnold as "saltation", while that characterized by rolling and sliding as "surface creep".

Wind velocities were measured with a Pitot tube and an alcohol manometer. In wind gradient determinations, 6 Pitot tubes and a multiple alcohol manometer were used. Six Robinson cup type anemometers connected to a single recording instrument were also used in the field. The

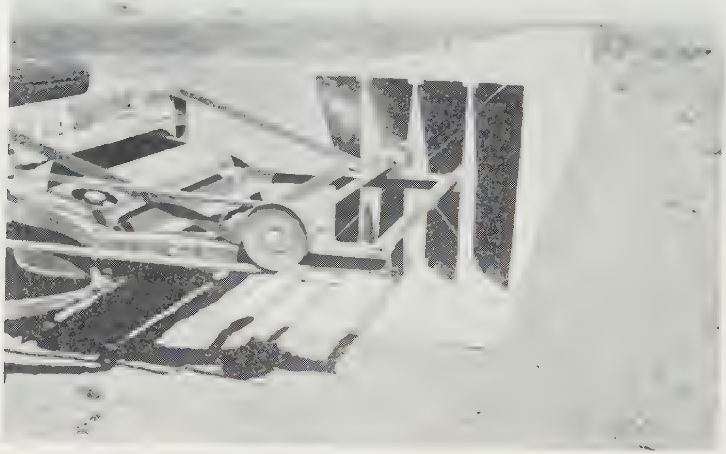

FIGURE 1. Portable field tunnel. Upper, windward end; lower, leeward end showing drifting of soil over fallow.

rate of soil flow in the laboratory tunnel was measured by the difference in the weight of the air-dry soil before and after exposure to the wind. In the portable tunnel measurements were made by differences in weight of the soil between exposures and also by two types of catchers, the Bagnold

sand catcher (3) and a specially constructed soil catcher. The relative efficiency of each type of catcher was determined by comparing the quantity of soil or sand caught with the quantity determined by the difference in the weight of the soil before and after exposure.

THE RELATION OF SOIL DRIFTING TO WIND VELOCITY GRADIENT

The experiment dealing with the effect of soil movement on wind velocity gradient was carried out in both wind tunnels and in the field. Readings of the wind velocity gradient and the rate of soil movement were first made under moderate to severe soil drifting. The eroding surface was then "fixed" with a fine spray of water, and wind velocity readings up to about 18 inches in height were again recorded. Figure 2 indicates some data obtained on freshly formed dune material derived from Hatton fine sandy loam. It was composed of air-dry, loosely deposited erosible particles of an average diameter of 0.18 mm., the largest not exceeding 0.83 mm. in diameter and the smallest composed of an appreciable quantity of dust less than 0.05 mm. in diameter. The results, being typical in so far as any other type of freshly deposited dry wind drift is concerned, are in perfect conformity with those obtained by Bagnold on desert sand and conform closely to the modified rate of flow formula which he proposed.

The solid lines in Figure 2 show the typical wind gradients over a "fixed" surface over which no soil movement took place, while the dotted lines indicate the velocity gradients when soil movement was in progress. The results obtained in the open field were essentially the same as those obtained at the leeward end of a 44-foot field tunnel. Readings made in the laboratory tunnel at the leeward end of a 15-foot length of exposed soil sample were typical only to about 4 to 5 inches in height, but due to limited length the velocity gradient above that height had not reached a complete equilibrium with the exposed surface.

The velocity readings in Figure 2 are plotted on a graph in which the ordinate is the logarithm of height. On a logarithmic scale the curve of a linear velocity gradient is a straight line. It will be observed that zero velocity is designated by a point 0 on the ordinate, to which all of the velocity curves over a "fixed" surface converge. The position of the point 0 lies at height k which, on the logarithmic graph for Hatton fine sandy loam wind drift, is seen to be 0.02 cm. This corresponds to a surface roughness of 30 times that height or 0.6 cm., which is actually the approximate height of the surface ripples formed previously by wind erosion. In Prandtl's equation the slope of a straight line on the logarithmic graph is expressed by $\sqrt{\frac{\gamma}{\rho}}$, which denotes the vertical wind gradient and is usually designated by $V*$. From it the actual drag caused by each unit area of any type of ground surface can be given by $\gamma = \rho V*^2$. Over any type of surface $V*$ is proportional to the velocity Vz, as measured at any height z, and is equal to Vz divided by $5.75 \log \frac{z}{k}$.

The dotted lines in Figure 2, on the other hand, represent the velocity gradients formed over a drifting soil surface. Over such a surface, wind velocities at all heights are reduced and new wind gradient curves are

established, all of which have a common velocity at height k^1. The new wind gradients, denoted by Bagnold as $V@$, are equal to $Vz - Vt$ divided by $5.75 \log \frac{z}{k^1}$.

Determinations of the vertical wind gradients over cultivated soils containing mixtures of both erosible and non-erosible fractions showed that a somewhat similar reduction of the wind velocity takes place over a drifting surface as compared to the velocity over the same surface "fixed" by a fine spray of water. This reduction in wind velocity does not appear to be as great as over dune materials containing erosible fractions only. Over cultivated fields the quantity of soil carried by wind does not reach the maximum that could be carried by wind of any definite velocity, except at the leeward part of some badly drifting fields. As a result of this, the decrease in the surface wind velocity caused by the saltating soil particles appears to be lessened somewhat, the actual amount of decrease varying directly with the amount of soil being carried by the wind.

RELATION OF WIND VELOCITY TO INTENSITY OF SOIL MOVEMENT

Over a loose ground surface composed only of erosible fractions such as of freshly formed, dry wind drifts, the rate of soil flow was found to increase rapidly with distance from the windward edge unt l a point was reached beyond which there was no more increase in the intensity of erosion. Under such a condition the distance required for soil movement to reach an equilibrium with the wind was found to be from 8 to 30 feet, depending on the average size and the size distribution of the particles carried. At equilibrium with the wind velocity gradient and the type of

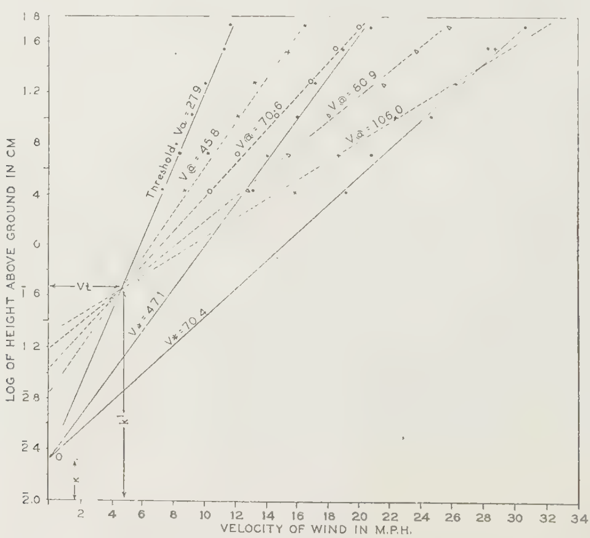

FIGURE 2. Wind velocity gradients over fine sandy loam dune, in a portable field tunnel. Dotted lines denote gradients over a drifting surface, solid lines over the same surface "fixed" with a fine spray of water. $Vt = 4.8$ m.p.h. or 214 cm./sec., $k = 0.02$ cm., $k^1 = 0.5$ cm.

surface, the rate of soil flow over freshly formed wind dunes conformed in most cases quite closely to Bagnold's finding on dune sand (3), namely, that the flow varies as the cube of $V@$. Bagnold found that the rate of sand flow q may be expressed by $q = C\sqrt{\frac{d}{D}}\,\frac{\rho}{g}\,V@^3$, in which C is a constant varying from 1.5 for sand of nearly uniform grain size to 2.8 for that of a wide range of size, d is the average diameter in cm. of grains carried, D is 0.025, ρ is the density of air, and g the gravity constant. It shows that for dune sand the rate of flow also varies as the square root of grain diameter. In this investigation it was not possible to check this relation on soils because of the difficulty in securing different sized soil grains of equal porosity and apparent specific gravity.

Typical data on the rate of soil flow over different types of dune materials are presented in Table 1. The wide variation in the value of C

TABLE 1.—RELATION BETWEEN WIND VELOCITY AND RATE OF FLOW OF DIFFERENT DUNE MATERIALS IN A PORTABLE FIELD TUNNEL

Average diameter d	$V@$	Vt	k^1	Rate of flow	C
cm.		cm./sec.		gr./cm./sec.	
Clean dune sand					
.022	39.6	278	.6	.124	1.70
.022	48.6	278	.6	.206	1.53
.022	54.4	278	.6	.290	1.82
.022	59.7	278	.6	.443	1.78
.022	72.7	278	.6	.832	1.85
.022	90.6	278	.6	2.044	2.34
.022	97.2	278	.6	2.502	2.30
Dune clay					
.044	49.3	228	.5	.101	.51
.044	69.5	228	.5	.331	.60
.044	89.5	228	.5	.671	.58
.044	109.0	228	.5	.986	.46
Dune fine sandy loam					
.018	45.8	214	.5	.100	.98
.018	60.7	214	.5	.246	1.03
.018	70.6	214	.5	.452	1.21
.018	80.9	214	.5	.849	1.52
.018	90.8	214	.5	1.553	1.96
.018	106.0	214	.5	2.530	2.00
Dune fine sandy loam					
.011	49.8	179	.2	.145	2.79
.011	71.5	179	.2	.591	2.88
.011	84.0	179	.2	.998	3.04
.011	103.5	179	.2	1.790	3.06

obtained on different types of wind drifts seems to be due to reasons other than the range of size distribution of the individual soil particles carried. Results with dune sand confirm those of Bagnold for velocity gradients up to $V@$ of 72.7, but for gradients above this value C increased somewhat. No reason can be given for the increased value of C at higher velocities. The results on dune clay show that the intensity of drifting varied as the cube of $V@$, but that the actual intensity, as indicated by the value of C, was considerably less than for sand. The table shows one case with fine sandy loam drift in which the rate of flow did not vary as the cube of $V@$. The value of C increased from 0.98 for $V@$ of 45.8 to 2.0 for $V@$ of 106.0. In another set of tests on practically the same type of dune material the rate of flow, as shown in Table 1, did vary as the cube of $V@$. The reason for the lack of this relation in the former case is not known, but it may possibly be due to the change in the moisture content of the dune material between exposures to the wind. Unfortunately the moisture content was not determined in these cases, although it is known that the material in the former case was somewhat dampened by a light rain a short time previous to exposure in the wind tunnel. Both materials contained at least 10% by weight of dust particles less than 0.05 mm. in diameter.

Attempts made to find the relation between wind velocity and the rate of flow over cultivated soils containing mixtures of erosible and non-erosible fractions failed because over such a condition the rate of flow was not constant, but changed with time, the rate of change depending on the length of the exposed area, the wind velocity, and the proportion of erosible to non-erosible fractions present. In the wind tunnel the intensity of soil drifting over a cultivated soil was rapid at first, but diminished with time and ceased after the surface became stabilized with fractions too coarse to be moved by the wind. The time required for movement to cease varied directly with the length of the exposed sample and the ratio of erosible to non-erosible fractions found in the exposed soil and inversely with wind velocity. Because of this it was concluded that the most suitable method of measuring the erosiveness of cultivated soils is to measure the quantity of soil erosible under some definite wind velocity.

INTENSITY OF SOIL DRIFTING IN RELATION TO THE SIZE OF THE AFFECTED AREA

Over ordinary cultivated soils comprising both erosible and non-erosible fractions, the increase in the intensity of drifting with distance extends to far greater distances than over dune materials containing only erosible fractions. Some data obtained over fields under fallow are presented in Table 2. The data show that over some fields the intensity of drifting as measured by the rate of soil flow up to 2 inches in height, gradually increased to as far as 450 yards from the windward edge. The distance required for drifting to reach its maximum intensity appears to vary widely on different fields; in many cases this increase extends up to the leeward edge of the drifting area.

The cause of increase in intensity of drifting with distance is not thoroughly understood, but it seems to be due, to some extent at least, to the steady accumulation of the erosible soil towards the leeward part of

TABLE 2.—THE INTENSITY OF SOIL DRIFTING AT DIFFERENT POSITIONS OVER FALLOW FIELDS*

Field 1		Field 2		Field 3		Field 4		Field 5	
Distance from windward edge	Amount drifted in 20 min.†	Distance from windward edge	Amount drifted in 20 min.†	Distance from windward edge	Amount drifted in 1 hour†	Distance from windward edge	Amount drifted in 10 min.†	Distance from windward edge	Amount drifted in 15 min.†
yds.		yds.		yds.		ft.		ft.	
50	36	50	23	40	118	60	4	50	78
100	396	100	64	80	145	120	9	150	125
150	408	150	169	120	283	180	53	250	265
200	481	250	486	160	326	240	88	350	282
250	630	350	490	200	409	300	116	450	233
300	570	450	597	240	465	§	200	550	211
350	732	550	608	295	1115	–	–	§	390
§	760	§	560	§	1620	–	–	–	–

* Fields 1 and 5 were on Haverhill loam, 2 on Sceptre clay, 3 on Cypress loam, and 4 on Haverhill fine sandy loam.
† The amount is in grams per ½-inch width and up to 2 inches in height.
§ Possible maximum.

fields, and it is this increased accumulation of erosible material among clods or other obstacles that tends to smooth out the exposed surface and to increase the quantity of moving soil. A reversal in wind direction seemed to produce, in some cases, a corresponding accumulation of drifts in the opposite direction. Some dry sieving analyses of the surface soil across large blocks of drifting summer-fallow showed somewhat greater quantities of erosible grains of soil toward the leeward sides, but over a few other fields no such accumulation was evidenced and yet the rate of soil flow towards the leeward side was greater than to windward. Tests showed that the increases of intensity of drifting with distance were not always uniform in character, the lack of uniformity being due largely, it appears, to slight variations in topography and the uneven distribution of plant residues over the ground surface; however, the upward trend in the severity of drifting has been observed on practically every drifting field.

The intensity of soil drifting towards the leeward side of large blocks of summer-fallow appears to approach that for dune materials formed over similar soil types. Charts have been prepared which show the approximate rate of soil flow over different major types of dune materials under different wind velocities. By comparing the rate of soil flow at different lateral positions across the drifting field with the rate of soil flow over a similar soil type in dune condition, one could estimate whether drifting over that particular field has reached its maximum intensity and where. These estimates must, of course, be regarded as merely approximate; first, because only an average wind velocity and not its degree of fluctuation can be determined fairly accurately in the field, and second, the assumption is made that the dry aggregate structure of the moving particles in the field is the same as that in dune formations with which it is compared. The possible maximum soil flow for each field was calculated, and is indicated in Table 2.

TABLE 3.—THE INTENSITY OF SOIL DRIFTING AT DIFFERENT DISTANCES TO LEEWARD OF STUBBLE IN A STRIP FARMING SYSTEM*

Distance to leeward of stubble†	Rate of soil movement in grams per ½-inch width and up to 2-inch height per 15 minute exposure	Distance to leeward of stubble†	Rate of soil movement in grams per ½-inch width and up to 2-inch height per 15 minute exposure
yds.		yds.	
10	3	120	28
30	17	150	57
60	25	180	138
90	31	Possible maximum rate	300

* Alternating 20-rod strips of fallow and short wheat stubble. Wind velocity ranged from 13.5 to 17.1 m.p.h. at 12-inch height. Soil—silt loam. The position 180 yards to leeward was 3 yards to windward of the next stubble strip.

† Distance was measured along the direction of the wind and not at right angles to the direction of the strips.

In strip farming the quantity of soil moved across a fallow strip was found, as shown in Table 3, to increase markedly with distance up to the windward side of the next cropped strip with which it is alternated. The increase in the rate of flow with distance to leeward of cropped or stubble strips is attributed to two causes, first, the cumulative intensity of soil drifting caused by slow shifting of the erosible material towards the leeward

TABLE 4.—THE INFLUENCE OF STUBBLE STRIPS ON THE AVERAGE WIND VELOCITY OVER THE ADJACENT 10-ROD FALLOW STRIPS

Exposure 1		Exposure 2		Exposure 3		Exposure 4		Exposure 5		Exposure 6	
Distance to leeward	Velocity *	Distance to leeward	Velocity *	Distance to leeward	Velocity †	Distance to leeward	Velocity †	Distance to leeward	Velocity †	Distance to leeward	Velocity †
ft.	m.p.h.	ft.	m.p.h.	ft.	m.p.h.	ft.	m.p.h.	ft.	m.p.h.	ft.	m.p.h.
14	16.9	11	16.1	22	13.2	11	12.7	14	10.3	14	10.2
70	17.3	56	17.0	112	13.9	56	13.4	70	10.9	70	10.5
141	20.0	112	17.4	224	14.3	112	13.9	141	11.1	141	10.6
233	20.4	186	17.7	370	14.4	186	14.1	233	11.2	233	10.6

* Considerable soil drifting.

† No soil drifting.

NOTES: Distance to leeward of stubble strips was measured along the direction of wind. Velocity measured at 12-inch height. Robinson cup type anemometers were used and length of exposure was usually not less than 4 hours.

side of the drifting area, and second, the diminishing sheltering effect away from the leeward of the stubble strip. Table 4 shows the usual reduction in wind velocity over fallow to the leeward of strips of standing wheat stubble. The reductions in wind velocity caused by stubble strips extend only from 50 to 250 feet, whereas the increases in the intensity of soil drifting, as shown in Table 2, extend over many times this distance. These data show plainly that the increase in the rate of soil movement with distance over fallow is not so much due to the diminishing sheltering effect

of the windward crop or stubble as to the cumulative effect of soil drifting. The decrease severity of soil drifting in strip farming appears to be due primarily to the decreased length of the exposed fallow rather than to the sheltering effect of the stubble strips. In fact, the evidence secured shows that the principal value of stubble strips lies in their use as barriers which trap the moving soil and thus decrease the cumulative intensity of soil drifting so commonly found over large fields of bare summer-fallow. The rate of increase of soil flow with distance appears to vary greatly with soil type and nature of the exposed surface. Because of this, strip farming may not be expected to be equally effective under all conditions.

SUMMARY

This investigation was undertaken to find the relations between wind velocity, intensity of soil drifting, and area and nature of the eroding surface.

The moving soil particles over any type of dune material influenced the vertical wind gradient the same way as the eroding sand particles studied by Bagnold, and conformed closely to the rate of flow formula which he developed. Somewhat similar results were obtained over drifting cultivated soil composed of both erosible and non-erosible fractions. The rate of soil flow over dry dune formations varied somewhat as the cube of the difference between the existent velocity and the threshold velocity. Over cultivated soils the rate of soil movement did not remain constant, but diminished with time and ceased after the surface became stabilized with soil fractions too coarse to be moved by the wind.

Over fields of bare fallow the intensity of wind erosion increased with distance in some cases to as far as 450 yards from the windward edge. The data obtained show that the increase in intensity of soil drifting with distance is not altogether due to the diminishing sheltering effect of the adjacent non-eroding areas, but mainly to the cumulative effect of soil drifting. In strip farming the principal value of alternating stubble strips seems to be in their use as barriers which trap the moving soil and thus decrease the cumulative intensity of soil drifting.

ACKNOWLEDGMENT

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RELATION OF WIND EROSION TO THE DRY AGGREGATE STRUCTURE OF A SOIL[1]

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INTRODUCTION

It is generally recognized that the severity of wind erosion is largely influenced by the size of the individual soil particles, or aggregates, located at the eroding surface. Some of these may exist as single grains of sand, others as aggregates of widely variable dimensions. Soils are seldom composed of uniform-sized particles but of mixtures of various sizes, which may range from large clods many centimeters in diameter down to a highly pulverized fraction. In soils composed of particles varying widely in size the larger ones offer a certain degree of protection to the smaller, which, if left unprotected, may readily be moved about by even a gentle wind. The exact degree of protection offered by different sized clods has not previously been investigated.

Bagnold's studies (1, 2, 3, 4) are some of the few conducted on the actual transport of material along the surface of the ground. They were limited to sand only, and to sizes not exceeding 1.5 mm. in diameter, dealing largely with the nature and intensity of movement of sand by wind and with the size-grading of sand produced by a variable velocity. This work serves as a valuable basis for further studies on the erosiveness of soils.

Udden (14), in an experiment in which different sized soil particles were thrown into air moving at 8 miles per hour, found that quartz particles of 0.1 mm. in diameter were borne up practically completely by the wind and concluded that this is the largest average size of quartz particle which can be sustained in the air and transported for many miles through the atmosphere. He also states (15) that the readily eroded particles of soil do not greatly exceed 0.5 mm. in diameter. No information is available in the literature to show what relation, if any, exists between the size of soil aggregates and the actual erosiveness of soils.

In this study it was sought to find what velocities of wind are required to move the various sized individual soil particles and what size of lumps, and the minimum quantities of these, should be present in order to offer the greatest degree of stability to the eroding surface. Previous work (6) showed that a suitable wind tunnel can be used to study the erosiveness of soils. Since it has been shown by various investigators (8, 10, 12) that the size of the soil aggregates can be altered to some extent simply by tilling the soil at some definite moisture content, it was hoped that this study would indicate the type of structure that should be induced in order best

[1] Part of a thesis submitted to the Graduate School of the University of Minnesota in partial fulfilment of the requirements for the degree of Doctor of Philosophy.
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to reduce the erosiveness. Further, the erosiveness of mixtures of various sized particles and clods, such as exist naturally in a soil, was determined, and there was finally formulated an expression, based on the dry sieving analysis, by which the erosiveness of any freshly tilled and uniformly mixed sample of soil may be evaluated.

EXPERIMENTAL PROCEDURE

The classes of soil materials used in this study were clay, clay loam, fine sandy loam, and clean sand. They were thoroughly air dried, passed through a nest of sieves, and stored in air-tight containers to be used as required. The sieves had square apertures with diameters of 0.05, 0.10, 0.15, 0.18, 0.25, 0.42, 0.59, 0.83, 1.19, 2.00, 6.36, 12.7, and 38.0 millimeters. Particles of the same composition as quartz sand but less than 0.05 mm. in diameter were obtained by grinding.

To test the erosiveness of the different soil materials, use was made of a return flow type wind tunnel with a test chamber 15 feet long, 2.5 feet wide, 2 feet high, and equipped with a 3-foot propeller driven by a variable speed electric motor. The velocity of wind, ranging from 7 to 37 m.p.h., could be easily controlled and quickly altered by a rheostat. The velocities were measured with a Pitot tube at various positions up to 12 inches above the surface. All velocity gradients up from 6 to 9 inches in height at the leeward end of the exposed area fitted well into Prandtl's logarithmic formula (9) which gives the velocity of any fluid near the boundary surface in terms of the magnitude of friction per unit area of surface, height of measurement above the surface, and size of the surface irregularities. The soil samples were exposed in a trough 12 feet long, 8 inches wide, and 2 inches high with open ends, built in two 6-foot sections and placed parallel to the length of the test chamber. For comparison, erosion trials were conducted with both 6- and 12-foot lengths of the exposed area. The soil to be exposed to the wind was placed in a trough and levelled in a layer of 0.25 to 1.75 inches in thickness, depending on the size of soil aggregates used. Precautions were taken to avoid having the material blown away to such a depth as to expose the floor of the trough.

The quantity of soil eroded during each test was determined by weighing the material before and after exposure to the wind. Some dust circulated through the tunnel, but none of it settled on the exposed soil or caused an abrasion. The larger particles carried in suspension and all the particles carried in saltation and surface creep[1] were trapped in the greatly enlarged return section of the tunnel. At least duplicated, and in most cases triplicated tests were made. During the course of the experiment the temperature of the air varied from about 21° to 24° C., and the barometric pressure from 690 to 700 mm. of mercury, variations negligible for all practical purposes.

Samples containing particles up to 3 mm. in diameter, on being placed in the wind tunnel, were first exposed for a short length of time to wind of velocity well above that required to initiate movement. The wind was then reduced to a low velocity and slowly increased until a point was reached at which erosion continued indefinitely. This velocity is termed

[1] The movement of particles in a series of leaps or bounces is known as *saltation*, and that characterized by rolling and sliding as *surface creep*.

by Bagnold (1) the *threshold velocity*, which denotes the minimum velocity required to produce a continuous movement of the material exposed to the wind. The same composite soil material was never exposed to the wind more than 3 times, except after complete re-sieving, while composite samples containing aggregates above 0.42 mm. were re-sieved after each individual test, this having to be done because of the marked size-grading effect of the wind.

A number of preliminary tests had to be made in determining the threshold velocity for different sized soil particles. Since these were never exactly of the same size in any 2 samples used, there was a range of velocity between the low point at which only the smallest particles could be removed and the high point at which there was a definite and continuous movement of all the sizes contained in the mixture. This range varied directly with that of the particle sizes present in the sample. At a low velocity the movement would cease when the surface became stabilized with a bed of coarser aggregates. Upon a slight increase of velocity, a further movement would take place and would continue only up to the time when the surface once again became stabilized with still coarser aggregates. Ultimately, a velocity was reached which was just high enough to move even the largest particles. Then the movement proceeded indefinitely. It was this velocity of the wind which was considered most important from the standpoint of soil drifting and which was recorded.

Soil aggregates greater than 3 mm. were not moved by even the highest velocity, which was about 37 m.p.h. at a 6-inch height. Such high surface velocities seldom occur in the field and are unimportant in such a study as this. Uniform mixtures of aggregates ranging from less than 0.05 mm. to 38 mm. were tested for susceptibility to drifting. Under this wide range of aggregate size there was no definite velocity that would perpetuate the movement of soil material. Even at the highest velocities the movement would continue only for a short time, ceasing after the surface had become stabilized with the coarser aggregates. There was, in other words, no available velocity at which movement of soil would continue indefinitely, as was the case with soil material composed of smaller particles only. For a very coarse structure of the soil it was not possible to say at what definite velocity soil drifting was initiated, even if it did not continue indefinitely. Slight amounts of dust would be raised even at fairly low velocities, but these points were too indefinite to record. The amount of dust raised increased steadily with increased velocity. A test of the susceptibility of this type of structure appeared limited to only one type of measurement—the quantity of soil eroded up to the time when the movement ceased, this measurement representing the quantity of soil erosible under some definite wind velocity. The time of exposure required to bring about a cessation of erosion varied considerably, depending on the type of clod structure, the velocity of wind, and the length of the exposed soil area.

Wind velocities of 17, 22, and 30 m.p.h. at 1-foot height were used in determining the erosiveness of complex mixtures of soil aggregates. A 17-m.p.h. wind at this height corresponds to a moderate wind in the open at which considerable drifting of the erosible soil usually becomes apparent. A 22-m.p.h. wind corresponds to a high natural wind, often accompanied by severe dust storms. A 30-m.p.h. wind at 1-foot height is rare in nature.

EXPERIMENTAL RESULTS

Threshold Velocities

Table 1 shows the lowest velocity of wind required to initiate and continue the movement of different sized soil particles. The most readily eroded particles ranged from 0.05 to 0.15 mm. in diameter. Above this range of size the threshold velocity increased with the increase in size, while below this range the threshold velocity increased as the size of particles decreased. Contrary to what was expected, particles less than 0.05 mm. in diameter were relatively resistant to wind erosion. It will be seen from Table 1 that for Cypress clay loam a 13.1 m.p.h. wind was required to induce the movement of particles less than 0.05 mm. in diameter, whereas only an 8.7-m.p.h. wind was required to move those of 0.05 to 0.1 mm. Even under 13.1-m.p.h. the movement of particles less than 0.05 mm. could hardly be detected under a strong beam of light and a much higher velocity than that recorded was required to cause a movement plainly visible to the naked eye. Much of this material was not transported as separate individual particles but as clusters which were often broken off at the irregularities of the surface and carried away by the wind. Typical saltation, as that observed by Bagnold (1) on drifting sand, could not be detected.

Particles less than 0.05 mm. produced by grinding sand were not transported by even a 37-m.p.h. wind. A comparison of this material with that obtained by sieving soils through a 0.05-mm. sieve showed that in the latter most particles ranged from 0.05 to 0.02 mm., whereas in the former many more were less than 0.02 mm. The ground particles also were more angular. These differences in size and shape were evidently the cause of such wide differences in the threshold velocities required. The threshold velocities for different sized particles sieved from Hatton fine sandy loam were practically identical with those for similar sizes from Cypress clay loam. Similar sizes of clean quartz sand, however, required somewhat greater threshold velocities. These differences correspond to the differences in the apparent specific gravity of the materials shown in Table 1. The length of the exposed sample, if beyond 6 feet, had little, if any, effect on the threshold velocity of the wind required.

The values obtained for grains of sand above 0.1 mm. in diameter agree closely with the existing theory (7, 11, 13), namely, that the size of the solid particle moved by any fluid varies as the square of the threshold velocity, the velocity being taken as that at the top of the grain resting on the surface. It is expressed by the formula (referred to hereafter as formula 1):

$$V^2 = A \frac{\alpha - \rho}{\rho} gd$$

in which V = the threshold velocity in cm. per second,
A = a constant,
α = the specific gravity of the grain,
ρ = the specific gravity of the fluid,
g = the gravity constant,
and d = the diameter of the grain in cm.

While the values for grains of sand agreed with the above formula, the results of the different sizes of soil aggregates show that the constant A in formula 1 varies with the apparent specific gravity of the aggregates used. Since in all soils the apparent specific gravity of grains decreased as the size of the grains increased, the constant A was found to vary proportionately. However, if α be used to signify the apparent specific gravity of the grains instead of the real specific gravity, the results agree well with the formula. The apparent specific gravity of the sand remains approximately constant for the whole range of grain size used and hence A remains constant for the whole range of size above 0.1 mm. no matter whether α denotes the real or the apparent specific gravity.

TABLE 1.—MINIMAL VELOCITIES OF WIND IN M.P.H. REQUIRED TO PRODUCE A CONTINUOUS MOVEMENT OF VARIOUS SIZES OF SOIL AND SAND PARTICLES*

Diameter of particles in mm.	Cypress clay loam			Hatton fine sandy loam			Clean sand		
	Apparent specific gravity	Length of exposed area		Apparent specific gravity	Length of exposed area		Apparent specific gravity	Length of exposed area	
		6 feet	12 feet		6 feet	12 feet		6 feet	12 feet
< .05	1.07	13.1	–	1.09	14.5	–	1.10	>37.0†	>37.0†
.05 – .10	1.14	8.7	8.5	1.13	–	8.7	1.43	9.7	9.0
.10 – .15	1.15	8.6	8.3	1.15	–	8.1	1.44	10.4	9.3
.15 – .18	1.08	9.1	9.0	1.18	9.6	9.1	1.43	10.7	10.6
.18 – .25	1.07	10.1	10.1	1.13	10.2	10.3	1.43	11.7	11.8
.25 – .42	1.05	12.3	12.5	1.00	12.0	12.0	1.46	14.5	14.3
.42 – .59	1.05	15.0	14.8	.99	14.0	13.8	1.49	18.8	18.6
.59 – .83	.99	18.0	17.5	1.01	17.0	17.1	1.46	22.8	22.1
.83 – 1.19	.98	20.0	20.5	.82	–	20.0	1.48	28.4	25.2
1.19 – 2.0	.96	24.8	25.0	.81	23.8	23 7	1.51	35.4	35.1
2.0 – 3.0	.91	28.7	30.4	.78	28.9	28.9	–	>37 0	>37 0

* Wind velocities at 6 inches above the eroding surface. Temperature during the course of the experiment varied between 21° and 24° C., pressure 690 to 700 mm. of mercury.
† There was no actual continuous movement even at this velocity. Sand was ground to obtain particles less than 0.05 mm. in diameter.

All the data in Table 1 were verified by formula 1, with α signifying the apparent specific gravity. When the wind velocities are measured at a 6-inch height the value of A in all cases is approximately 10.8. This value does not hold for particles less than 0.1 mm. in diameter, and particularly for particles less than 0.05 mm., for which it is much higher. The very high value of A for the smallest particles indicates that their resistance to wind erosion is due to causes other than their size and apparent specific gravity.

Table 2 shows the minimal velocities required to produce a continual movement of mixtures of various sized soil particles. The velocity required varied directly with the average size of all of the component particles; the greater the percentage of coarse fractions in a mixture the greater was the velocity required to produce a continual movement. In other words, the threshold velocity for a mixture of different sized grains was lower than that required to erode only the largest of the grains. Thus, to produce the movement of clay loam granules of 0.42 to 0.58 mm. in diameter, a velocity of 14.8 m.p.h. was required (Table 1), but when it was mixed with 6 times its weight of smaller particles a velocity of 13.2 m.p.h. was required.

TABLE 2.—MINIMAL VELOCITIES OF WIND IN M.P.H. REQUIRED TO PRODUCE A CONTINUOUS MOVEMENT OF MIXTURES OF VARIOUS SIZES OF SOIL PARTICLES*

Size and quantity of constituent particles†	Cypress clay loam		Hatton fine sandy loam
	Length of exposed area		Length of exposed area
	6 feet	12 feet	12 feet
a	13.1	13.2	14.5
a and *b*, equal quantities	10.6	11.0	11.8
a to *c*, equal quantities	8.6	9.4	9.7
a to *d*, equal quantities	10.0	9.0	9.3
a to *e*, equal quantities	9.9	10.0	10.4
a to *f*, equal quantities	10.4	11.8	11.7
a to *g*, equal quantities	12.6	13.2	13.6
a to *h*, equal quantities	14.1	14.1	14.3
a to *i*, equal quantities	15.4	16.1	16.2
a to *j*, equal quantities	17.9	18.2	19.3
a to *k*, equal quantities	24.5	22.8	24.2

* Wind velocities at 6-inch height.
† *a* = < .05 mm. in diam.
b = .05 – .10 mm. in diam.
c = .10 – .15 mm. in diam.
d = .15 – .18 mm. in diam.
e = .18 – .25 mm. in diam.
f = .25 – .42 mm. in diam.
g = .42 – .59 mm. in diam.
h = .59 – .83 mm. in diam.
i = .83 – 1.19 mm. in diam.
j = 1.19 – 2.0 mm. in diam.
k = 2.0 – 3.0 mm. in diam.

These results should apply in considering the erosiveness of soils in the field, since it is known that these are seldom, if ever, composed of a single size of aggregate. Fractions which when alone were too coarse to be transported by wind of a definite velocity were transported freely when mixed with smaller particles, their movement being facilitated by the bombardment received from the smaller particles moving in saltation. The coarser material provided most of the surface creep.

Particles less than 0.05 mm. in diameter hindered the movement of the coarser grains mixed with them (Table 2). As a result of such hindrance the threshold velocity was increased proportionately. The threshold velocity varied directly with the relative quantity of the fine material present in the mixture and inversely with the size of its particles.

Erosiveness of Complex Mixtures of Different Soil Aggregates

With ordinary soils containing a certain proportion of coarse, non-erosible fractions, the movement of erosible material, once started, did not continue indefinitely under any velocity of wind but ceased as soon as the surface became protected by the coarser aggregates. For this reason it was decided that the method of measuring the erosiveness of such mixtures is the determination of the quantity of soil removed by wind up to the time when movement ceased. The time required for movement to cease varied inversely with the velocity of wind and the quantity of the non-erosible

fractions, and directly with the length of the exposed area. For convenience the different sized particles and clods used in these experiments were designated as follows:

Erosible fraction	A =		< .42	mm. in diameter
Erosible fraction	B =	.42 –	.83	mm. in diameter
Non-erosible fraction	C =	.83 –	2.0	mm. in diameter
Non-erosible fraction	D =	2.0 –	6.4	mm. in diameter
Non-erosible fraction	E =	6.4 –	12.7	mm. in diameter
Non-erosible fraction	F =	12.7 –	38.0	mm. in diameter

Typical results obtained on the relation existing between erosiveness and the different mixtures of soil aggregates are shown in Figures 1 to 10.

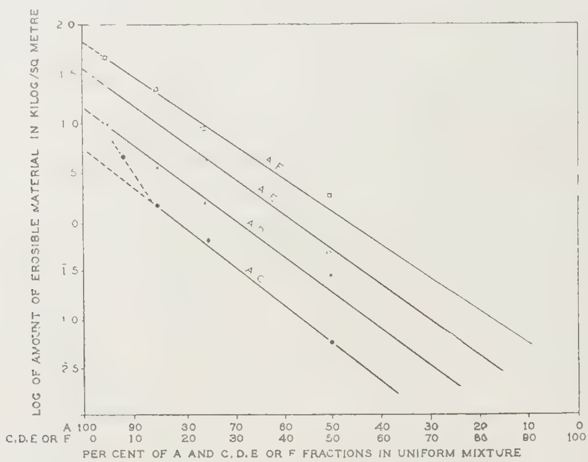

FIGURE 1. The influence of the non-erosible fractions C, D, E, and F, on the erosiveness of A under a 17 m.p.h. wind. Cypress clay loam. Length of exposed area 6 feet.

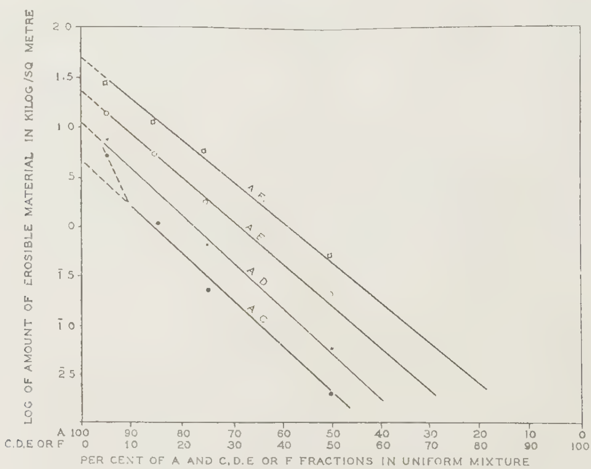

FIGURE 2. The influence of the non-erosible fractions C, D, E, and F, on the erosiveness of A under a 22 m.p.h. wind. Sceptre clay. Length of exposed area 12 feet.

A striking feature in these results is the existence of a logarithmic relation between erosiveness and the ratio of erosible to non-erosible fractions present in uniform mixtures. The two soil types used gave approximately the same results.

Figure 1 shows an example of the quantities of material in kilograms per sq. metre removable from uniform mixtures of different sized aggregates under a 17 m.p.h. wind. A typical example of the results for a 22 m.p.h. wind is shown in Figure 2, and likewise for a 30 m.p.h. wind as indicated in Figure 3. In all these experiments only one erosible fraction, *A*, was mixed with different amounts of the non-erosible fractions *C*, *D*, *E*, and *F*. Fraction *B* eroded less readily than fraction *A* at all velocities used. Fraction *C* was erosible only under velocities approaching and exceeding 30 m.p.h.

On the logarithmic graph it will be seen that the curves *AC*, *AD*, *AE*, and *AF* for any wind velocity are essentially parallel to each other, showing that the effect of *C*, *D*, *E*, and *F* in reducing the logarithm of amount of erosion of *A* is approximately constant for any given mixture exposed to a definite velocity. Under a 17 m.p.h. wind it was found that the curves *AC*, *AD*, *AE*, and *AF* meet the ordinate on the average at 0.60, 1.02, 1.40, and 1.74, respectively, which, on the numerical scale, represent the values of 3.98, 12.65, 25.10, and 55.0, respectively. Assuming the effect of *C* in preventing erosion of *A* to be unity, the effect of *D*, *E*, and *F* under a 17 m.p.h. wind is 0.380, 0.158, and 0.072, respectively.

As the wind velocity was increased, the effect of the coarser fractions in preventing erosion of *A* likewise increased. Thus, under a 22 m.p.h. wind, assuming the effect of *C* to be unity, that for *D*, *E*, and *F* fractions was increased to 0.425, 0.194, and 0.102, respectively; while under a 30 m.p.h. wind, assuming the effect of *D* to be unity, that for *E* and *F* became 0.491 and 0.252, respectively.

In Figures 1 and 2 it will be observed that the logarithmic relation does not hold for a mixture of fractions *A* and *C* when the content of the latter is less then 15% of the total. The logarithmic curve breaks near this point and shoots upward. Under a 17 m.p.h. wind a certain amount of movement of *C* commenced as its percentage was reduced to about 10%. In the proportions mentioned both *A* and *C*, therefore, became erosible

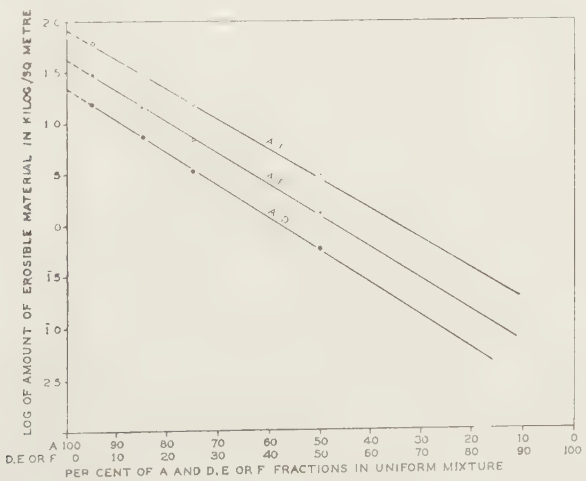

FIGURE 3. The influence of the non-erosible fractions, *D*, *E*, and *F*, on the erosiveness of *A* under a 30 m.p.h. wind. Cypress clay loam. Length of exposed area 6 feet.

but while A moved freely with the wind, C moved at a much lower rate, so that finally its content over the eroding surface was raised to a point where it was no longer moved by the wind.

The smallest quantity of any non-erosible fraction that was mixed with A was 5%. It is not known how much farther up the scale the logarithmic relation exists. In fact, the values shown on the ordinate when the content of C, D, E, or F is zero are false. At this point movement of A did not cease but became continuous and uniform in rate. Theoretically as the proportion of the non-erosible fractions approaches zero, the erosiveness of any mixture of A with C, D, E, or F should approach some fixed value characteristic of A and not the four different values as the extrapolated curves seem to indicate. But since the quantities of the non-erosible materials for which definite values were not determined are so small, they have no practical significance.

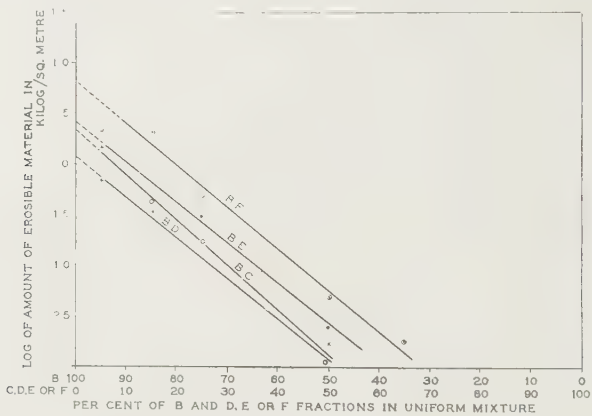

FIGURE 4. The influence of the non-erosible fractions C, D, E, and F, on the erosiveness of B under a 17 m.p.h. wind. Sceptre clay. Length of exposed area 6 feet.

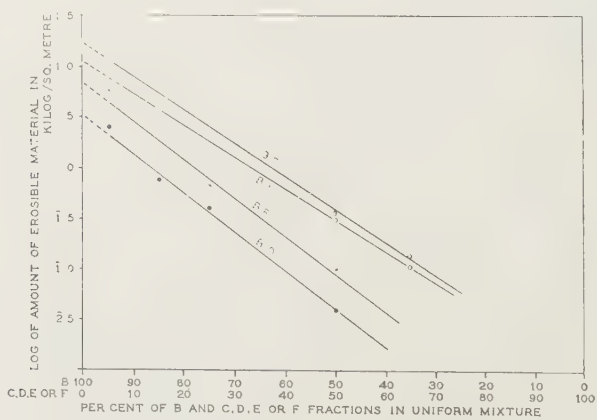

Figure 5. The influence of the non-erosible fractions C, D, E, and F, on the erosiveness of B under a 22 m.p.h. wind. Sceptre clay. Length of exposed area 6 feet.

While the position of the logarithmic curves indicates the effect of any of the non-erosible fractions in preventing the removal by wind of any erosible fraction, the slope of the curves, on the other hand, indicates how much a unit weight of the non-erosible material will reduce the amount of soil that would be blown off. Since the logarithmic curves follow a straight line, each unit of the non-erosible material added to some erosible fraction would reduce the logarithm of amount of erosion in equal proportions, a fact which will be made use of in computing the erosiveness of complex mixtures of soil aggregates.

A table was prepared by averaging the values of all plotted data to show to what extent the logarithm of erosiveness of soils is reduced by 1% of *C*, *D*, *E*, or *F* fractions when mixed uniformly with fraction *A*. The average reductions of the logarithmic values, together with the relative effect of each of the non-erosible fractions in reducing the erosion of *A*, are given in Table 3. The values in Table 3 make it unnecessary to consult

TABLE 3.—THE RELATIVE ABILITY OF THE NON-EROSIBLE FRACTIONS TO PREVENT THE EROSION OF A

	17 m.p.h. wind				22 m.p.h. wind				30 m.p.h. wind		
	C	*D*	*E*	*F*	*C*	*D*	*E*	*F*	*D*	*E*	*F*
Reduction of the logarithmic value by 1% of non-erosible fraction	.052	.048	.045	.041	.041	.039	.037	.035	.034	.033	.031
Relative effect in preventing drifting of *A*	1.00	.380	.158	.072	1.00	.425	.194	.102	1.00	.491	.252
Position of the log curve on the ordinate	.60	1.02	1.40	1.74	.86	1.23	1.57	1.85	1.36	1.67	1.96

the graphs in order to find the erosiveness of the different mixtures. Thus, the amount of material, in kilog./sq. metre of surface, removable from a uniform mixture of *A* 75%, *D* 25%, under a 17 m.p.h. wind, is:

$$\text{Antilog}\left(1.02 - \frac{D}{A+D} \times 100 \times 0.048\right) \text{ or}$$

$$\text{Antilog}\left(1.02 - \frac{D}{A+D} \times 4.8\right) = 0.66 \text{ kilog./sq. metre.}$$

Under a 22 m.p.h. it is:

$$\text{Antilog}\left(1.23 - \frac{D}{A+D} \times 3.9\right) = 1.79 \text{ kilog./sq. metre,}$$

while under a 30 m.p.h. wind it is:

$$\text{Antilog}\left(1.36 - \frac{D}{A+D} \times 3.4\right) = 3.23 \text{ kilog./sq. metre.}$$

Figures 4 to 6 show the results obtained when the erosible fraction *B* was mixed with different individual fractions. The existence of a logarithmic relation, as with fraction *A*, is evident. Furthermore, the logarithmic

curves correspond in slope approximately to the slope of those in which *A* is the erosible fraction. Only the position of these curves is altered. For any given wind velocity, therefore, a unit quantity of fraction *C*, *D*, *E*, or *F*, mixed with *B*, lowers the logarithmic value on the ordinate to the same

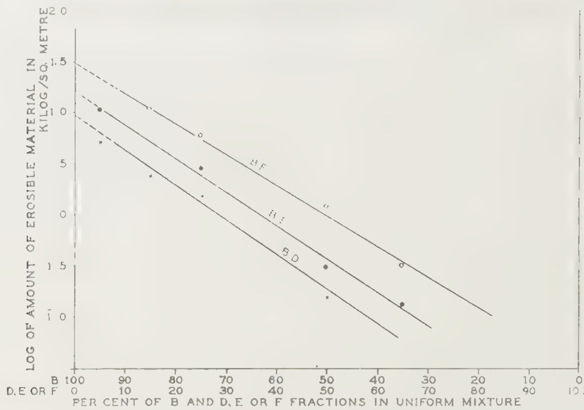

FIGURE 6. The influence of the non-erosible fractions *D*, *E*, and *F*, on the erosiveness of *B* under a 30 m.p.h. wind. Sceptre clay. Length of exposed area 9 feet.

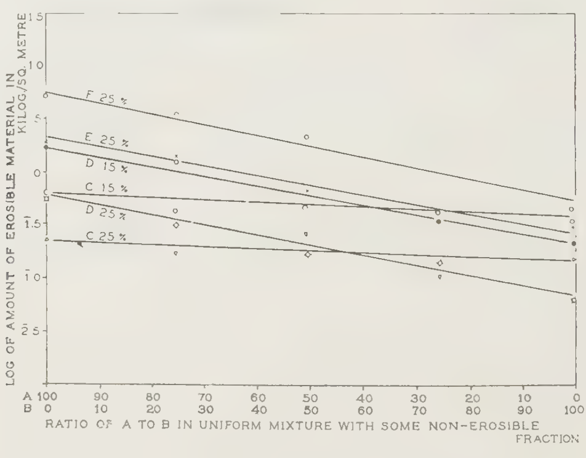

FIGURE 7. The influence of the non-erosible fractions *C*, *D*, *E*, and *F*, on the erosiveness of different mixtures of *A* and *B* under a 17 m.p.h. wind. Sceptre clay. Length of exposed area 6 feet.

extent as when these fractions are mixed with fraction *A*. The values for any mixture of *A* and *B*, as shown in Figure 10, also run parallel on the logarithmic scale to those in which pure *A* or pure *B* is used.

Figures 7, 8, and 9 show what happens when different mixtures of *A* and *B* (both erosible fractions) are mixed in turn with some non-erosible material. Here again the relation is logarithmic, so that all plotted curves become straight lines. As the ratio of *B* to *A* increases, the logarithm of the amount of erosible material decreases equally for *D*, *E*, and *F*. As the

velocity is increased the decrease of the logarithmic value caused by fraction *B* becomes less. It is computed from Figures 7, 8, and 9 that when *A*, in mixture with any quantity of a non-erosible fraction *D*, *E*, or *F* is replaced by *B*, the logarithm of the amount of erosible material is decreased by 0.96 under a 17 m.p.h. wind, by 0.76 under a 22 m.p.h. wind, and by 0.45 under a 30 m.p.h. wind. If only part of fraction *A* is replaced by *B* the logarithm of the amount of erosible material is decreased proportionately.

The same relation does not hold for fraction *C*. When *A*, in mixture *C*, is replaced by *B*, the logarithm of the amount of erosible material is reduced by only 0.30 under a 17 m.p.h. wind (Figure 7), but under a 22 m.p.h. wind the replacement of *A* by *B* actually increases the logarithmic value by 0.42 (Figure 8), while under a 30 m.p.h. wind *C* becomes erosible and moves freely with the other erosible fractions. It appears that fraction *B* has a greater abrasive action on *C* than *A* has, thus causing a certain amount of movement of *C*, particularly of the smaller particles falling within the range of size of this fraction. The slight temporary movement of *C* allows for exposure of a greater quantity of the erosible fractions to

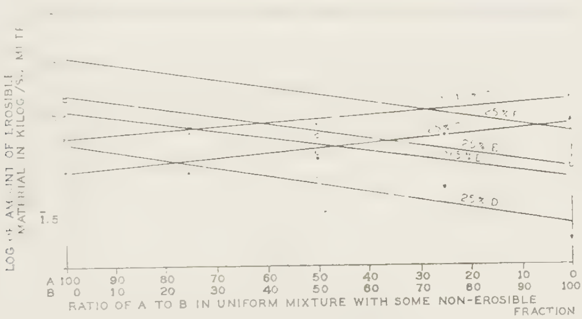

FIGURE 8. The influence of the non-erosible fractions *C*, *D*, *E*, and *F*, on the erosiveness of different mixtures of *A* and *B* under a 22 m.p.h. wind. Sceptre clay. Length of the exposed area 6 feet.

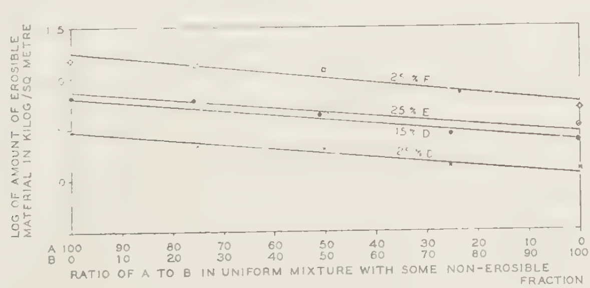

FIGURE 9. The influence of the non-erosible fractions *D*, *E*, and *F* on the erosiveness of different mixtures of *A* and *B* under a 30 m.p.h. wind. Sceptre clay. Length of exposed area 6 feet.

the wind, thus increasing the erosiveness of the mixture. From the plotted curves it can be determined to what extent the erosiveness is increased or decreased by the addition of definite quantities of *B* to *A* mixed with any quantity of some non-erosible fraction (Table 4).

TABLE 4.—CHANGES IN EROSIVENESS CAUSED BY REPLACING A BY B IN MIXTURE WITH ANY QUANTITY OF SOME NON-EROSIBLE FRACTION

Wind velocity	Increase (+) or decrease (−) of the logarithm of amount of erosible material caused by replacing *A* by *B* in mixture with			
	C	*D*	*E*	*F*
m.p.h.				
17	−0.30	−0.96	−0.96	−0.96
22	+0.42	−0.76	−0.76	−0.76
30	—	−0.45	−0.45	−0.45

What applies to the influence of *B* on erosiveness also applies to the influence of *C* when this becomes erosible under a strong enough wind, as shown in Figure 10. Under a 30 m.p.h. wind the replacement of *A* and *B* (in mixture with any quantity of *D*, *E*, or *F*) by *C* reduces the logarithmic value on the ordinate by 1.4, while a partial replacement of *A* and *B* by *C* reduces the logarithm of the amount of erosible material proportionate to the percentage replaced.

The results of the above experiments show the existence of a logarithmic relation between erosiveness and the quantity of any one or more erosible fractions uniformly mixed with any one or more of the non-erosible fractions. It is also shown that each non-erosible fraction has a definite effect in preventing erosion, irrespective of what erosible fraction or fractions are present in the mixture. Mathematical formulae can now be worked out by which the erosiveness of any mixture of the different sized soil fractions, as indicated by dry sieving analysis, may be determined.

To begin with, let it be assumed that the mixture contains only the erosible fraction *A* mixed with any, or all, of the non-erosible fractions *C*, *D*, *E*, or *F*. If it contains only one non-erosible fraction such as *C*, then, as the content of *C* approaches, zero, the erosiveness of the soil in kilog./sq. metre, under a 17 m.p.h. wind, will approach the antilog of 0.60 (Table 3),

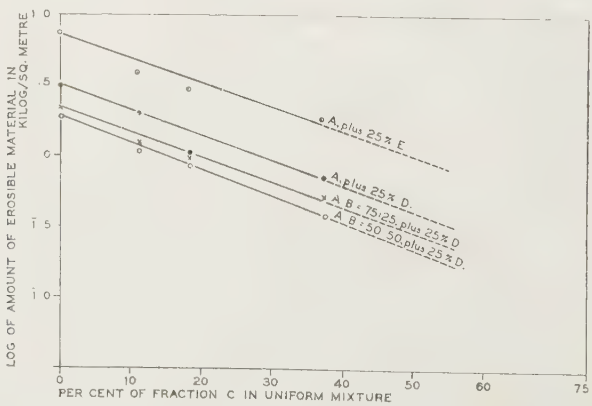

FIGURE 10. The influence of the non-erosible fractions *D* and *E* on the erosiveness of different mixtures of *A*, *B*, and *C* under a 30 m.p.h. wind. Sceptre clay. Length of exposed area 6 feet.

while if it contains any one of the fractions D, E, or F the maximum erosiveness, as indicated by points at which the extrapolated curves meet the ordinate, will approach the antilog of 1.02, 1.40, or 1.74, respectively. If the soil contains more than one non-erosible fraction, then the maximum amount of erosible material will be designated by the mean weighted position at which the logarithmic curves AC, AD, AE, etc., will meet the ordinate. This mean position will depend not only upon the position where each curve meets the ordinate, but also upon the slope of each curve and upon the proportion of each of the non-erosible fractions present in the mixture.

Let it be assumed that the soil in question is composed of erosible fractions A 40%, B 20% and non-erosible fractions C 15%, D 10%, E 10%, and F 5%. Disregarding, for the present, the influence of B on erosiveness, the average position where the extrapolated logarithmic curves will meet the ordinate will be at

$$\frac{\%C(.60)(.052) + \%D(1.02)(.048) + \%E(1.40)(.045) + \%F(1.74)(.041)}{\%C(.052) + \%D(.048) + \%E(.045) + \%F(.041)}$$

This is equal to 1.015 on the logarithmic scale. Assuming the position of the extrapolated curves on the zero ordinate to be correct, the erosiveness of this soil, when the quantity of fractions C, D, E, and F approaches zero, will approach the antilog of 1.015 or 10.35 kilog./sq. metre.

If, instead of only A, the erosible portion of the mixture contains both A and B, the logarithmic curve would meet the ordinate lower than at 1.015, the actual position depending on the ratio of B to A in the mixture. Since the replacement of A by B, when the whole mixture is composed of A, B, and C, will lower the position of the logarithmic curve by 0.30, 1% of B mixed with 99% of A will lower it by 0.003. On the other hand, if the non-erosible fraction is D, E, or F instead of C, then the replacement of A by B will lower the position of the curve by 0.96, as shown in Table 4.

Since, in the mixture in question, 20 parts of B are mixed with 40 of A, the logarithm of amount of erosible material under a 17 m.p.h. wind when the content of C, D, E, and F, fractions approaches zero, must be reduced to $1.015 - \left(0.30\frac{C}{C+D+E+F}\ \frac{B}{A+B}\right) - \left(0.96\frac{D+E+F}{C+D+E+F}\ \frac{B}{A+B}\right) =$ 0.777.

Let us suppose that only the 15 parts of C are mixed with 40 parts of A and 20 of B. Then the logarithm of erosiveness, as designated on the logarithmic scale, would be reduced by $4.1\ \frac{C}{A+B+C} = 0.821$. Should 10 parts of D be added to the preceding mixture, the logarithm of erosiveness would be further decreased by $3.9\ \frac{D}{A+B+C+D}$, while the addition of 10 parts of E and 5 of F would still further reduce the logarithmic value by $3.7\ \frac{E}{A+B+C+D+E}$ and $3.5\ \frac{F}{A+B+C+D+E+F}$ respectively. It does not matter whether we assume that the first addition

to the A and B mixture is C, D, E, or F, the final value would be approximately the same. The erosiveness of the above mixture under a 17 m.p.h. wind would then be:

Antilog $(0.777 - 0.821 - 0.459 - 0.39 - 0.175) = 0.085$ kilog./sq. metre.

Complete equations can now be written for the erosiveness of any mixture under three different wind velocities.

Under a 17 m.p.h. wind the average position of the logarithmic curve on the ordinate would fall at $\frac{.60S + 1.02T + 1.40U + 1.74V}{S + T + U + V}$ when $0.052C = S$, $0.048D = T$, $0.045E = U$, and $0.041F = V$. Assuming that

$$5.2\frac{C}{A + B + C} = W,$$

$$4.8\frac{D}{A + B + C + D} = X,$$

$$4.5\frac{E}{A + B + C + D + E} = Y,$$

$$4.1\frac{F}{A + B + C + D + E + F} = Z,$$

and the amount of erosible material in kilog./sq. metre $= q$, then

$$q\ (17\text{ m.p.h.}) = \text{antilog}\left[\frac{0.60S + 1.02T + 1.40U + 1.74V}{S + T + U + V} - \left([illegible]\frac{C}{C + D + E + F}\frac{B}{A + B}\right) - \left(0.66\frac{D + E + F}{C + D + E + F}\frac{B}{A + B}\right) - W - X - Y - Z\right] \quad (2)$$

Under a 22 m.p.h. wind the average position of the logarithmic curve on the ordinate would fall at $\frac{.86S + 1.23T + 1.57U + 1.85V}{S + T + U + V}$ when $0.041C = S$, $0.039D = T$, $0.037E = U$, and $0.035F = V$. Assuming that

$$4.1\frac{C}{A + B + C} = W,$$

$$3.9\frac{D}{A + B + C + D} = X,$$

$$3.7\frac{E}{A + B + C + D + E} = Y,$$

$$3.5\frac{F}{A + B + C + D + E + F} = Z, \text{ then}$$

$$q\ (22\text{ m.p.h.}) = \text{antilog}\left[\frac{0.86S + 1.23T + 1.57U + 1.85V}{S + T + U + V} - \left([illegible]\frac{C}{C + D + E + F}\frac{B}{A + B}\right) - \left(0.76\frac{D + E + F}{C + D + E + F}\frac{B}{A + B}\right) - W - X - Y - Z\right] \quad (3)$$

For a 30 m.p.h. wind the average position of the logarithmic curve on [illegible] would lie at $\frac{1.36T + 1.67U + 1.96V}{T + U + V}$ when $0.034D = T$, $0.033E = U$, and $0.031F = V$. Assuming that

$$3.4\,\frac{D}{A + B + C + D} = X,$$

$$3.3\,\frac{E}{A + B + C + D + E} = Y,$$

$$3.1\,\frac{F}{A + B + C + D + E + F} = Z, \text{ then}$$

$$[illegible]\ (30 \text{ m.p.h.}) = \text{antilog}\left[\frac{1.36T + 1.67U + 1.96V}{T + U + V} - \left(0.45\,\frac{B}{A + B}\right) - \left(1.4\,\frac{C}{A + B + C}\right) - X - Y - Z\right] \qquad (4)$$

TABLE 5.—COMPARISON OF DETERMINED WITH CALCULATED EROSIVENESS OF MIXTURES OF SOIL AGGREGATES FROM CYPRESS CLAY LOAM. LENGTH OF THE EXPOSED SOIL AREA—6 FEET

[illegible] soil aggregates in uniform [illegible]	Quantities of erosible soil in kilog./sq. metre					
	17 m.p.h. wind		22 m.p.h. wind		[illegible]	
	Determined	Calculated	Determined	Calculated	Determined	Calculated
A 65%, B 20%, C 15%	60	[illegible]	1.90	[illegible]	–	–
A 55%, B 30%, C 15%	56	[illegible]	1.62	[illegible]	–	–
A 65%, B 15%, C 10%, D 10%	.40	[illegible]	1.40	[illegible]	[illegible]	6.62
A 55%, B 15%, C 15%, D 15%	17	[illegible]	.68	[illegible]	[illegible]	[illegible]
A 55%, B 20%, C 10%, D 10%, [illegible]	29	[illegible]	1.04	[illegible]	[illegible]	[illegible]
A 40%, B 30%, C 25%, D 5%	06	[illegible]	57	[illegible]	[illegible]	[illegible]
A 40%, B 20%, C 10%, D 10%, E 10%, F 10%	06	[illegible]	20	2	[illegible]	[illegible]
A 33⅓%, B 33⅓%, C 33⅓%	.02	[illegible]	51	5	–	–
A 30%, B 30%, C 30%, D 10%	.01	[illegible]	17	[illegible]	[illegible]	[illegible]
A 30%, B 20%, C 15%, D 15%, [illegible]	.01	T	[illegible]	[illegible]	[illegible]	[illegible]
A 25%, B 25%, C 25%, D 25%	T	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A 25%, B 25%, C 25%, D 15%, E 10%	T	T	[illegible]	[illegible]	[illegible]	[illegible]
A 20%, B 20%, C 15%, D 15%, E 15%, F 15%	T	T	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

In Table 5 a comparison is made of the experimentally determined amounts of material blown off the different uniform mixtures of soil aggregates with the amounts calculated according to the above equations. Considering the nature of the experiment and the magnitude of the probable error that is likely to occur both in preparation of the samples and in exposure of the soil to the wind, the agreement is good.

The study was carried out further to check the validity of the equations on soils as found under field conditions. In Table 6 the determined erosiveness of freshly cultivated soils is compared with the erosiveness computed from the dry sieving analyses. With few exceptions, the two sets of values agree fairly closely. The equations appear to afford an approximate measure of the susceptibility of freshly cultivated and uniformly mixed dry soils to wind erosion.

TABLE 6.—COMPARISON OF DETERMINED WITH CALCULATED EROSIVENESS OF VARIOUS TYPES OF CULTIVATED SOILS*

Soil type	Quantity of erosible soil in kilog./sq. metre					
	Determined in wind tunnel			Computed from dry sieving analysis		
	17 m.p.h. wind	22 m.p.h. wind	30 m.p.h. wind	17 m.p.h. wind	22 m.p.h. wind	30 m.p.h. wind
Hatton fine sandy loam	1.51	2.96	11.00	1.91	4.55	13.05
Haverhill clay loam	.29	.96	5.50	.33	1.41	6.37
Haverhill light loam	.27	.89	5.43	.26	.96	5.17
Haverhill loam	.23	.90	3.88	.24	.86	4.46
Regina heavy clay	.05	.18	3.17	.04	.22	2.88
Fox Valley silty clay loam	.07	.63	2.48	.07	.31	2.66
Sceptre clay	.01	.03	1.34	T	.04	1.30

* The dry aggregate structure of the soils at the time of exposure to the wind in the wind tunnel was:

	>38.0	38.0–12.7	12.7–6.36	6.36–2.0	2.0–.83	.83–.42	<.42 mm.
Hatton fine sandy loam	0	.2	.9	5.0	4.5	6.1	83.3
Haverhill clay loam	0	.5	2.6	7.4	12.6	16.8	60.1
Haverhill light loam	0	9.6	4.6	7.0	8.7	12.1	58.0
Haverhill loam	4.8	8.8	3.7	7.9	7.9	5.3	61.6
Regina heavy clay	0	.8	7.3	6.8	19.8	33.3	32.0
Fox Valley silty clay loam	0	3.2	5.1	13.9	14.4	5.2	58.2
Sceptre clay	0	0	1.1	12.2	39.4	18.7	28.6

DISCUSSION

In this paper the study of the relation between erosiveness and the dry aggregate structure is divided into two distinct parts, the first dealing with mixtures in which all the fractions are erosible and the second with mixtures of erosible with non-erosible fractions. The largest soil aggregate that could be moved along the surface of the ground by a high wind was found to be about 2.0 mm. in diameter, this requiring a wind of about 30 m.p.h. measured at 12 inches above the surface. This corresponds to 50 to 70 m.p.h. at 50 feet, the height at which most of the meteorological data pertaining to wind are recorded. The second part, dealing with mixtures of erosible with non-erosible fractions, has received a more detailed study because such is the structural condition generally found on wind eroded cultivated soils.

The present accepted theory as to the threshold velocity required to move the various sizes of grains seems to apply very closely to clean sand in which the apparent specific gravity is the same for all sizes of grains. It also applies to soil aggregates if the apparent specific gravity remains the same; but the soil studied showed that the aggregates markedly decreased in their apparent specific gravity as their size was increased, thus reducing the minimum velocity of wind required to move them.

Bagnold (1) found that the results on sand agree more closely with the threshold velocity theory when the velocity is measured at a height equal to the height of the surface ripples (k^1) produced by drifting sand instead of at some fixed height. In this study, even when the velocity was measured at a 6-inch height, it was found that the results agree with the threshold velocity theory, but only for grains above 0.1 mm. in diameter. Bagnold (3) suggested that the great resistance of very fine materials, such as Portland cement, to wind erosion is due to forces of cohesion acting against the force of wind. The present study indicates that finely pulverized soil materials have similar properties with respect to wind erosion. While the common belief, that the more pulverized a soil is the more susceptible it is to wind erosion is justified to only a certain degree, it does not apply to particles much less than 0.05 mm. in diameter. However, in a natural dry soil such small particles seldom exist as such, but group themselves into larger, more or less stable individual aggregates or into a hard, compacted mass. For all practical purposes, therefore, it is probably not incorrect to say that the more a natural soil is pulverized, as by tillage machinery, the greater will be its susceptibility to wind erosion. Very finely ground soil material would acquire an entirely different property.

The presence of large amounts of individual silt and clay particles in a soil appears to cause the formation of a compact, massive structure which, while quite resistant to wind erosion, may present a serious structure problem otherwise. Bradfield and Jamieson (5) state that hard and intractable soils are usually those largely composed of fine silt having a single grain structure.

The experiments indicate that the greatest degree of protection for a soil against wind erosion is offered by that size of soil aggregate which is just large enough not to be moved by wind of a definite velocity. Thus, under wind velocities up to about 25 m.p.h. measured at 1-foot height, aggregate *C* (0.83–2.0 mm.) offered the greatest degree of protection, but under higher wind velocities it became erosible and lost its protective value. The most protective fraction under velocities above 25 m.p.h. is, therefore, aggregate *D* (2.0–6.4 mm.) which will not erode even under an exceptionally high wind.

The value of fraction *B* (0.42–0.83 mm.) in reducing the erosiveness of the soil appears significant. Thus, when the erosible fraction *A* (<0.42 mm.), mixed with any quantity of fractions *D*, *E*, or *F*, was replaced entirely by the erosible fraction *B*, the erosiveness of the mixture under a 17 m.p.h. wind (as may be calculated from the data in Table 4) was reduced by approximately 90%. Under a 22-m.p.h. wind this reduction amounted to 83%, and under a 30 m.p.h. to 65%.

Although the soil types used in the study of the relation between erosiveness and the dry aggregate structure gave similar results, it is not possible to conclude definitely that all soils will do the same. It is expected that the general principles found in these experiments will hold true for all soils, although the values of the different constants may vary somewhat. To what extent they may vary can be determined only by similar experiments with other soil types. The apparent specific gravity, particularly of the erosible fractions, and the average diameter of the various fractions and other factors may have a distinct effect on the values of the different constants used in calculating the erosiveness of soils. It should be pointed out also that the conclusions on the relation of the dry aggregate structure to erosiveness apply only when the various fractions are uniformly distributed throughout the surface layer of soil, a condition commonly found in freshly cultivated soils, but not usually in soils that have been left untilled for some time. For this reason the dry sieving analysis cannot be regarded as an absolute means by which the inherent erosiveness of soils may be measured.

SUMMARY

1. The object of the study was to find what relation exists between the wind erosiveness of soils and their dry aggregate structure. For this purpose, use was made of a return flow type wind tunnel in which velocities up to 37 miles per hour at 6-inch height could be produced.

2. The minimum velocity of wind required to initiate and continue the movement, known as the threshold velocity, was least for particles 0.05 to 0.15 mm. in diameter, these requiring a velocity of 8 to 9 m.p.h. at 6 inches above the ground. Above this range of size the threshold velocity increased with the increase in size of grains, while below that it increased with the decrease in size of grains. The threshold velocities for grains above 0.1 mm. were found to vary as the square root of their diameter and inversely with their apparent specific gravity. Particles below 0.05 mm. were highly resistant to wind erosion for reasons other than their size or their apparent specific gravity.

3. In uniform mixtures containing coarse, non-erosible fractions, the movement of erosible material under any velocity of wind ceased as soon as the surface became protected by coarser aggregates. In such mixtures the amount of soil removable under a definite wind velocity was found to vary logarithmically with the ratio of erosible to non-erosible fractions present. It was further determined that the greatest degree of protection of a soil against wind erosion was given by that size of aggregate which is just large enough not to be moved by the wind. On the basis of the results obtained, mathematical equations were formulated by which the erosiveness of any uniform mixture of soil aggregates may be evaluated.

4. These equations, based on the dry sieving analysis of the soil, seemed to afford an approximate measure of the susceptibility of freshly cultivated and uniformly mixed dry soils to wind erosion, but not of soils that have been left untilled for some time or have otherwise formed a surface crust following a rain. It was concluded that the dry aggregate structure, as determined by dry sieving analysis, cannot be regarded as a single criterion by which the inherent erosiveness of soils may be determined.

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INVERTASE IN PLANTS AS A MEASURE OF AVAILABLE SOIL NITROGEN[1]

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In his book on Enzyme Chemistry, Tauber (7) states that sucrase (saccharase, invertase) "Occurs in the small intestine of mammals and in the tissues of certain animals and plants. Sucrase hydrolyzes cane sugar into fructose and glucose. It may be obtained in a relatively pure state from yeast, which is a very good source. Sucrase is quite a stable enzyme."

In 1927, Doby and Hibbard (1) carried out some experiments to study the effect of lack of certain salts or ions on the enzyme activity in plants. Using sugar beets as a test crop, they showed that the quantities of amylase and saccharase (the two enzymes studied) were greater in the leaves of plants grown in a potassium-deficient solution than in a complete nutrient solution. The saccharase activity was determined by measuring in a polariscope the degree of inversion of a standard sucrose solution brought about by the enzyme preparation. It is stated (3) that "hardly any data had been available till then on the question of how the amount of enzymes is influenced by inorganic nutrients."

In a study of potassium deficiency in sugar cane, Hartt (4) noted that the invertase activity in the blades was greater in the control than in the potassium-deficient plants. It was further observed that potassium may increase or decrease the enzyme activity of plants, or have no effect thereon, and the effect varies with the kind, age, and the organ of the plant studied. Later work by the same author (5) has shown that, when tested unbuffered, the invertase activity of the plants deficient in K was weaker than that of the controls, in both blades and stems, but when tested at optimum reaction (pH 4.4), the invertase activity was equal in all the blades, but not in the stems, although the difference between extremes was less. Hartt measured the activity of the invertase by the increase, during 24 hours, in the ability to reduce Fehling's solution.

Further work by Doby (3) showed that, with young shoots of rye, a deficiency of potassium caused the enzyme content to rise to a high figure; a deficiency of phosphorus caused hardly any change in the enzyme content; but a deficiency of nitrogen resulted in a considerable reduction in the invertase content, and a certain proportionality was shown between the degree of nitrogen nutrition and the invertase content of the plants. Based on this obervation, Doby (2) has devised a method in which the invertase content of rye seedlings grown according to the Neubauer technique is used as a measure of the available soil nitrogen. He has formulated a proportional number which he calls the "Nitrogen Number" and which is determined in the following way: samples of the soil to be examined are placed in two Neubauer units and the rye seeds planted in the usual way; to one of these units, a complete nutrient solution is added, while for the other,

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a nitrogen-free nutrient solution is used; when the rye seedlings are 17 days old, the plants are cut off at the base of the stalks, a portion of them ground up with water, and the resultant suspension used to hydrolyze cane sugar solution under controlled conditions. The reaction constant is found from polarimetric readings of aliquots removed from the hydrolyzing solution at definite time intervals, and the nitrogen number (Nn) calculated according to the equations:

$$k = \frac{1}{t \,.\, 0.4343} \log \frac{\alpha_0 - \alpha_\infty}{\alpha - \alpha_\infty}$$

$$If \,.\, 0 \,.\, 10^3 = \frac{k \,.\, \text{grams cane sugar}}{\text{grams dry matter}}$$

$$Nn = \frac{100 \,.\, If_{-N}}{If_T}$$

Where

k = reaction constant
t = time in minutes
α_0 = initial angle of rotation
α_∞ = infinite angle of rotation
α = angle of rotation determined at time t.
If = Invertase concentration
If_{-N} = the invertase concentration of rye plants receiving nutrient solution without nitrogen
If_T = the invertase concentration of rye plants receiving complete nutrient solution.

If *Nn* is small, the nitrogen condition of the soil is poor and its nitrogen requirement is great; if *Nn* is large, sufficient available nitrogen is present in the soil and none need be added. Thus it can be seen that this method gives an indication of the amount of nitrogenous fertilizer that would be required by a soil and, if found to be generally applicable, should prove to be of great assistance in soil investigations. It was therefore decided to begin an investigation into the possibilities of this method, to see what results could be obtained under our conditions.

Since it is claimed by Doby (3) that potassium has the opposite effect to nitrogen on the invertase content of plants, and since other workers have obtained somewhat different results with other plants on the effect of potassium on invertase activity, it was decided to begin the investigation with a study of the effect of the three common fertilizing elements, N, P, and K, singly and in combinations, on the invertase activity of rye seedlings.

Using sand only in the Neubauer dishes, 24 units were planted with 100 rye seeds each. The treatments used were N, P, K, NP, NK, PK, NPK, and check, so that each treatment was run in triplicate. The nutrients were added in solutions, made up as follows:

For N—1.074 g. $NaNO_3$ per litre.
For P—0.870 g. $NaH_2PO_4 \,.\, H_2O$ per litre.
For K—2.310 g. K_2SO_4 per litre.

Combinations contained these weights of materials dissolved separately, mixed, and then made to one litre.

To start the germination of the rye seeds, 60 cc. of the desired solution (for the check, 60 cc. of distilled water) was added to each dish, which was then placed in the Neubauer chamber. Distilled water was added every day or two to compensate for evaporation. At the end of 17 days, the rye seedlings were cut off at the base of the sprouts and chopped into short lengths. The growth of the plants was so arranged that one individual planting of rye matured about every 3 or 4 days.

Five grams of this chopped material were then weighed out, ground in a porcelain mortar with a small amount of sand, transferred with distilled water to a 25 cc. volumetric flask, and made up to the mark. This was used as the enzyme suspension.

A sugar solution was made up by dissolving 6.5 grams of sucrose in 96 cc. of a buffer solution made from 43 cc. of normal sodium acetate and 57 cc. of normal acetic acid per litre. Five cubic centimeters of this sugar solution were placed in each of a series of 50 cc. weighing bottles with ground glass stoppers, and to each was added 1 cc. of the enzyme suspension. These were then incubated in a chamber at 38° C.

After 10, 20, 30, 40, 50, 60, 90, 120, and 240 minutes, the action of the enzyme was stopped by the addition of 5 cc. of 10% NaOH. The solutions were then clarified by adding 1 cc. of saturated neutral lead acetate solution and 2 cc. of saturated NaH_2PO_4 solution, and filtering.

Table 1. Invertase activity of rye seedlings receiving different treatments*

Individual readings

Time of incubation (minutes)	Check (H_2O)			N			P			K		
10	5.10	4.45	4.47	5.60	4.69	4.83	4.45	4.50	5.00	4.37	5.30	4.51
20	7.65	6.57	6.50	7.80	8.10	8.27	6.67	6.70	7.80	6.93	8.77	7.37
30	9.05	8.48	8.73	10.50	9.60	10.00	8.15	8.70	10.20	9.20	11.70	10.20
40	10.7	10.0	10.4	12.7	11.4	11.6	10.0	11.4	11.6	10.6	13.7	12.7
50	12.7	11.6	12.7	15.1	13.2	12.7	11.4	12.5	14.0	12.5	15.9	14.0
60	14.7	12.7	14.7	17.5	16.5	15.6	12.4	14.0	15.6	14.0	18.7	15.6
90	20.0	17.5	18.6	22.2	20.0	21.1	16.8	18.6	20.7	19.2	25.4	21.5
120	24.3	21.5	24.3	29.5	24.1	28.0	21.1	23.4	26.7	28.0	31.9	28.0
240	38.3	36.8	43.1	46.7	42.5	46.7	35.0	41.3	43.7	46.7	53.7	46.7
	NP			NK			PK			NPK		
10	6.36	5.83	6.60	5.00	4.84	4.65	5.00	4.31	5.20	5.40	5.00	5.60
20	10.80	9.87	10.30	8.70	9.00	8.23	7.57	8.22	8.70	9.35	7.00	8.60
30	12.30	12.50	13.40	11.60	11.60	10.00	9.35	11.20	10.80	14.00	8.80	10.80
40	15.6	15.6	16.1	15.6	14.0	13.7	13.3	14.0	13.6	16.5	11.6	15.1
50	18.4	18.7	17.5	17.5	17.5	15.6	14.7	15.6	16.0	18.7	12.7	17.5
60	21.2	20.0	20.0	20.0	19.3	17.5	16.5	17.6	17.5	21.5	14.9	20.0
90	27.0	26.7	26.4	28.0	26.6	23.3	23.3	22.5	22.1	28.0	18.7	26.4
120	33.3	33.0	35.0	35.0	33.0	31.1	28.0	25.5	26.6	35.0	23.3	35.0
240	54.0	54.0	56.0	54.0	58.3	46.5	43.2	40.0	46.6	46.5	35.0	46.6

* Results in mgm. glucose per cc. enzyme suspension.

TABLE 2.—INVERTASE ACTIVITY OF RYE SEEDLINGS RECEIVING DIFFERENT TREATMENTS*

Time of incubation (min.)	Check (H_2O)	N	P	K	NP	NK	PK	NPK	Significant difference 5% point	Significant difference 1% point	Standard error in %
10	4.67	5.04	4.65	4.73	6.26	4.83	4.84	5.33	0.68	0.93	7.7
20	6.91	8.06	7.06	7.69	10.32	8.64	8.16	8.32	1.21	1.67	8.6
30	8.75	10.03	9.02	10.37	12.73	11.07	10.45	11.20	2.12	2.92	11.7
40	10.4	11.9	11.0	12.3	15.8	14.4	13.6	14.4	2.1	2.8	9.2
50	12.3	13.7	12.6	14.1	18.2	16.9	15.4	16.3	2.6	3.6	10.3
60	14.0	16.5	14.0	16.1	20.4	18.9	17.2	18.8	3.1	4.2	10.4
90	18.7	21.1	18.7	22.0	26.7	26.0	22.6	24.4	4.2	5.8	10.8
120	23.4	27.2	23.7	29.3	33.8	33.0	26.7	31.1	5.3	7.3	10.8
240	39.4	45.3	40.0	49.0	54.7	52.9	43.3	42.7	7.4	10.2	9.3

* Mean of triplicate determinations.

Preliminary investigation had shown that the use of the polarimetric method of determining invertase activity was not particularly satisfactory and it was finally decided to adopt the dinitrosalicylic acid method of Sumner and Howell (6). In this method, the glucose formed on inversion of the sucrose is measured colorimetrically and the invertase activity is expressed as milligrams of glucose produced per cubic centimeter of enzyme suspension. The procedure was therefore to transfer 1 cc. of each of the filtrates (obtained after inversion and clarification) to a 25 cc. volumetric flask, together with 3 cc. of the dinitrosalicylic acid reagent. The colour was developed by heating to 100° C. one-half hour and the solutions, after cooling, were made to the mark and compared in a colorimeter with glucose standards of known strength.

It has been indicated above that the purpose of this experiment was to study the effect of the three common fertilizing elements, N, P, and K, singly and in combinations, on the invertase activity of rye seedlings. The determinations were run in triplicate so that some idea of the variation to be expected might be obtained. By allowing the time for inversion to extend over periods ranging from 10 minutes to 4 hours, it was hoped that the optimum time of inversion, if any, would be shown. The complete set of results, which are presented in detail in Table 1, were submitted to statistical analysis, and in Table 2 are presented the averages of the results for each triplicate set of rye plants, together with the values for significant difference at the 5% point, which can be considered as significant, and the values for significant difference at the 1% point, which can be considered as highly significant. The values for the standard error expressed as percentage of the mean of all 8 treatments, which are given in the last column, are directly comparable for each period of incubation and show that the 10-minute incubation time appears to give the best agreement between replicates. There is, however, very little difference between the value for any one incubation time and that for any other.

In order to study the effect of added nitrogen on the invertase activity of the rye seedlings, the values obtained from those plants receiving nitrogen are compared with those from plants receiving no nitrogen, i.e., N with

check, NP with P, NK with K, and NPK with PK. The differences between the averages shown in Table 2 are presented in Table 3, together with the values for significant differences at the 5% point and at the 1% point. From these figures, it is clearly seen that when N is compared

TABLE 3.—COMPARISON OF AMOUNTS OF GLUCOSE PRODUCED ON INVERSION BY PLANTS RECEIVING N AND THOSE NOT RECEIVING N*

Time of incubation (minutes)	N – O	NP – P	NK – K	NPK – PK	Significant difference 5% point	Significant difference 1% point
10	.37	1.61	.10	.49	.68	.93
20	1.15	3.26	.95	.16	1.21	1.67
30	1.28	3.71	.70	.75	2.12	2.92
40	1.5	4.8	2.1	.8	2.1	2.8
50	1.4	5.6	2.8	.9	2.6	3.6
60	2.5	6.4	2.8	1.6	3.1	4.2
90	2.4	8.0	4.0	1.8	4.2	5.8
120	3.8	10.1	3.7	4.4	5.3	7.3
240	5.9	14.7	3.9	−0.6	7.4	10.2

* Differences between the averages given in Table 2.
NOTE—Underlined once—significant.
Underlined twice—highly significant.

TABLE 4.—COMPARISON OF AMOUNTS OF GLUCOSE PRODUCED ON INVERSION BY PLANTS RECEIVING P AND THOSE NOT RECEIVING P*

Time of incubation (minutes)	P – O	NP – N	PK – K	NPK – NK	Significant difference 5% point	Significant difference 1% point
10	−.02	1.22	.11	.50	.68	.93
20	.15	2.26	.47	− .32	1.21	1.67
30	.27	2.70	.08	.13	2.12	2.92
40	.6	3.9	1.3	0	2.1	2.8
50	.3	4.5	1.3	− .6	2.6	3.6
60	0	3.9	1.1	− .1	3.1	4.2
90	0	5.6	.6	−1.6	4.2	5.8
120	.3	6.6	−2.6	−1.9	5.3	7.3
240	.6	9.4	−5.7	−10.2	7.4	10.2

* Differences between the averages given in Table 2.
NOTE.—Underlined once—significant.
Underlined twice—highly significant.

with check, and NPK with PK, there are no significant differences; when NK is compared with K, there are significant differences in two cases only (after 40 and 50 minutes of incubation); but when NP is compared with P, the increase in invertase activity due to the combination NP is in every case not only significant but highly significant.

In Table 4, figures similar to those in Table 3 are given to show the effect of added phosphorus on the invertase activity of the rye seedlings. These show that when P is compared with check and PK with K, there are no significant differences; when NPK is compared with NK, there is a significant decrease in one case (after 240 minutes of incubation); but

TABLE 5.—COMPARISON OF AMOUNTS OF GLUCOSE PRODUCED ON INVERSION BY PLANTS RECEIVING K AND THOSE NOT RECEIVING K*

Time of incubation (minutes)	K − O	NK − N	PK − P	NPK − NP	Significant difference 5% point	Significant difference 1% point
10	.06	− .21	.19	− .93	.68	.93
20	.78	.58	1.10	−2.00	1.21	1.67
30	1.62	1.04	1.43	−1.53	2.12	2.92
40	1.9	2.5	2.6	−1.4	2.1	2.8
50	1.8	3.2	2.8	−1.9	2.6	3.6
60	2.1	2.4	3.2	−1.6	3.1	4.2
90	3.3	4.9	3.9	−2.3	4.2	5.8
120	5.9	5.8	3.0	−2.7	5.3	7.3
240	9.6	7.6	3.3	−12.0	7.4	10.2

* Differences between the averages given in Table 2.
NOTE—Underlined once—significant.
Underlined twice—highly significant.

when NP is compared with N, the increase in invertase activity due to the combination NP is significant in every case, and highly significant in 4 of the 9 cases.

The figures showing the effect of added potassium on the invertase activity of the rye plants are given in Table 5. When K is compared with check, there are significant differences in 2 cases (after 120 and 240 minutes of incubation); when NK is compared with N, there are significant differences in 5 cases (after 40, 50, 90, 120, and 240 minutes of incubation); and when PK is compared with P, there are significant differences in 3 cases (after 40, 50, and 60 minutes of incubation). On the other hand, when NPK is compared with NP, there are highly significant decreases due to K in 3 cases (after 10, 20, and 240 minutes of incubation).

These results presented in Tables 3, 4, and 5 therefore seem to indicate that, under the conditions of this experiment, although none of these three elements alone has any pronounced influence on the invertase activity

of rye seedlings, the combined effect of nitrogen and phosphorus does bring about a significant increase in invertase activity over the treatment of nitrogen alone and phosphorus alone, as well as the untreated sample. In fact, results for the NP treatment show a highly significant increase over all other treatments after both 10 and 20 minutes of incubation.

The reason for the beneficial effect of this combination is not obvious. It is suggested that it may be due to the stimulation of root development by the phosphorus, though there is no direct evidence to support this suggestion. It should be emphasized that the results reported in this paper deal with a preliminary investigation only. They point, however, to the necessity of further investigation of the combined effects of nitrogen and phosphorus on the invertase content of rye seedlings and the extension of this study to plants grown in soils as well as in sand cultures. It is hoped that results of such a study will be reported in a future paper.

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BOOK REVIEW

"Legislative Protection and Relief of Agriculturist Debtors in India" by K. G. Sivaswanvy, B.A., 390 pages with select bibliography. Gokhale Institute of Politics and Economics, Poona, India. Publication No. 6, 1939. (Price Rs. 4.)

At the outset the author delimits the scope of his book to those matters concerned with "the protection and relief which legislation could give to the agriculturists to prevent the growth of unproductive debts and the evil results arising out of them". Results of the existing rural credit system are listed as follows: (1) Undue exploitation of the needs of an ignorant debtor; (2) The accumulation of irredeemable debt; (3) The passing of land into the hands of money-lenders.

The author draws attention to the changes in land transfer rights in India under British rule and reviews various legislative measures enacted to relieve the indebtedness of landlords and to regulate the transfer of agricultural lands. In the latter connection consideration is also given to the regulation of temporary transfer of lands through mortgages. In dealing with the regulation of money-lending, attention is given to control of the interest rate and to means whereby the practices of money lenders have been regulated. Debt adjustment is discussed at length with particular reference to the operation of debt conciliation boards under the various acts.

The author's experience in rural co-operation and welfare work has fitted him admirably for the task of analyzing the measures which have been taken for the relief of the agricultural debtor in India from the standpoint of the agriculturist classes. He can perhaps be excused for what might seem to some readers as somewhat of a bias towards the debtor, when the gravity of the rural debtor problem is appreciated. The situation as viewed by the author can perhaps best be summed up by quoting his concluding sentence, "Whatever form the credit machinery may take, its purpose should be to convert the deficit economy of the peasant into a surplus one, and to find labour for the unemployed agricultural population."

While covering in great detail the measures affecting the agricultural debtor in India, the material is presented in an interesting manner and the book commends itself to anyone interested in the problem of a debt-ridden agricultural population.

—S. C. Hudson.